

1  
2  
3  
4  
5  
6 A NASA Earth Science Enterprise Implementation Plan for  
7 Energy and Water Cycle Research:  
8

9  
10  
11 ***“Predicting Energy and Water Cycle  
12 Consequences of Earth System Variability and  
13 Change”***  
14

15  
16  
17 Prepared by the NASA Energy- and Water-  
18 Cycle Study (NEWS) Science Integration Team  
19  
20  
21  
22  
23  
24  
25  
26

27  
28 November 8, 2004  
29 Draft Version 1.6

# Table of Contents

## *Predicting Energy and Water Cycle Consequences of Earth System Variability and Change*

<b>Table of Contents</b>	<b>2</b>
<b>Executive Summary</b>	<b>3</b>
<b>1 Program Overview</b>	<b>6</b>
<b>2 Current Capabilities and Development Objectives</b>	<b>13</b>
2.1 Current Observational Resources, Capabilities and Examples of Deficiencies	13
2.2 Current Modeling Resources, Predictive Capabilities and Examples of Deficiencies	16
2.3 Current Application and Consequence Capabilities and Deficiencies	19
<b>3 Key Energy and Water Cycle Research Challenges</b>	<b>21</b>
3.1 Key Components of the Global Energy and Water Cycle	21
3.2 Key Tools for Energy and Water Cycle Research	25
3.3 Key Application Benefits from NEWS	39
<b>4 Elements of the NEWS Implementation Plan</b>	<b>42</b>
4.1 Phase 1: Exploiting Current Capabilities and Preparing for the Future	43
4.2 Phase 2: Integrating Essential Improvements into the Observation-Prediction System	46
4.3 Phase 3: Completing and Validating the Water Cycle Prediction System	49
<b>5 Linkages to NASA, National and International Programs</b>	<b>52</b>
5.1 Linkages with Other NASA Programs	52
5.2 Interagency Partnerships	61
5.3 International Partnerships	64
<b>6 Management</b>	<b>66</b>
6.1 NEWS Program Management	66
<b>Appendices</b>	<b>68</b>
A.1 NEWS Science Integration Team	68
A.2 References	70
A.3 Acronyms	71

## Executive Summary

Our life on Earth is dependent on water and our economic, political and social systems will be greatly affected by alterations in the global energy and water cycle, particularly regional precipitation regimes, and extreme hydrologic events, such as floods and droughts. From an overall Earth Science perspective, the key questions are to what extent expected climate changes are related to changes in the rate of the Earth's energy and water cycles, and what trend may be predicted in the future. The energy and water cycle is driven by a multiplicity of complex processes and interactions, many of which are inadequately understood and poorly represented in climate models. Earth is the only planet in the Solar System where water exists freely in three states: liquid, vapor and solid ice. The transformations among the three states is very complex and require an understanding of moisture and energy storages and exchanges between and within the Earth's atmosphere, oceans, land, and biological systems over a wide range of space and time scales.

The scientific framework for the *Water and Energy Cycle focus area* is outlined in the NASA Earth Science Enterprise Strategy document, issued in October 2003. It is one of six focus areas that define the scientific content of the NASA Earth Science Program, and includes both research and technology components. Its implementation is planned through NEWS (NASA Energy and Water cycle Study), a coordinated research program, whose central goal is “*to document and enable improved, observationally-based, predictions of energy and water cycle consequences of Earth system variability and change.*”

When implemented, the proposed NEWS research program will yield significant advances and breakthroughs in hydrological cycle climate science. Progress in achieving its objectives will be measured against its success in making significant advances in:

- **Development and deployment of an experimental energy and water cycle global observing system**
- **Documenting the global energy and water cycle through an observational record of all associated geophysical parameters**
- **Building a fully interactive global climate model that encompasses the process-level forcings on and feedbacks within the global energy and water cycle**
- **Creating a global land and atmosphere data assimilation system for energy and water variables**
- **Assessing the variability of the global energy and water cycle on time scales ranging from seasonal to decadal, and space scales ranging from regional to continental to global**
- **Supporting the application of climate prediction capabilities for estimating the impact of climate variability and climate changes on water resources over a variety of spatial and temporal scales**

The broad national objectives of energy and water related climate research extend well beyond the purview of any single agency or program, and call for the support of many activities that are matched to each agency's respective roles and missions. NASA has the experience and expertise to support the full range of investigations, from global-remote sensing to point-scale field observations, global data acquisition, and the development of prediction systems that can



1 assimilate these measurements. Therefore, to achieve the ultimate goal of operational global  
2 change predictions and applications across all significant scales NASA will seek collaborations  
3 with other Federal agencies, in particular the National Oceanic and Atmospheric Administration  
4 (NOAA), National Science Foundation (NSF), Department of Energy (DoE), U.S. Geological  
5 Survey (USGS), Department of the Interior (DoI), the Department of Agriculture (DoA), the  
6 scientific community-at-large and private industry. Such collaborations include experimental and  
7 operational observations and analysis tools for characterizing air/sea fluxes, ocean circulation,  
8 atmospheric state, land surface vegetation, sub-surface hydrology, snow and ice among others;  
9 as well as support for the development of new general circulation models and end-to-end  
10 prediction systems. In some cases, NASA investments may be required to supplement these  
11 activities to ensure that they meet specific needs, for example, *in situ* measurements of  
12 parameters that are essential to validating space based remote sensing, as well as quantities  
13 needed but not otherwise measured or derived.

14 The NASA /NEWS research linkage to the international science community is primarily through  
15 the World Climate Research Programme (WCRP), especially the Global Energy and Water  
16 Experiment (GEWEX), but includes several complimentary elements of Climate Variability and  
17 Predictability (CLIVAR) and Climate and Cryosphere (CLIC). GEWEX has overall WCRP  
18 responsibility for providing an international interface with all the national space agencies  
19 concerning energy and water cycle related global climate research requirements, instruments,  
20 data, and science support. Other international connections include those with the International  
21 Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Program  
22 (IHDP).

23 Implementation of the NEWS program is planned in three phases as described in Chapter 4, each  
24 successive phase being focused on a range of research activities, as described in Chapter 3 and  
25 represents advances beyond the current status of observations, modeling and applications as  
26 summarized in Chapter 2. The next-generation prediction system will be based on a global  
27 observing and assimilation system to determine the initial state of climate (especially external  
28 and internal forcings) and a modeling system to make the forecast, neither of which currently  
29 exist in complete or accurate form. Developing the prediction capability requires progressing  
30 through a iterative cycle of research elements: observations, analysis, model development and  
31 testing, evaluation, and demonstration of applications. The development of observing/data  
32 analysis system capabilities evolves in parallel with the program's research efforts to further  
33 develop prediction models and applications.

34 The emphasis during **Phase-1** is to exploit current capabilities and prepare for future  
35 developments of NEWS program elements. **Phase-2** focuses on addressing deficiencies and  
36 building a viable "prediction" system. **Phase-3**, focuses on the delivery of an end-to-end system  
37 to address the ESE vision, namely: comprehensive observations to accurately quantify the state  
38 and variability of the global water cycle, including time series data sets with no major gaps;  
39 routine analysis of variability in storage, transports and fluxes of water ; routine prediction of  
40 key water cycle parameters (including clouds, precipitation, radiation interactions, energy  
41 budgets, and surface hydrological variables), and improved forecasts for use in water  
42 management and decision making.

43 It is envisioned that the NEWS program will build upon existing NASA-supported basic  
44 research in atmospheric physics and dynamics, radiation, climate modeling, and terrestrial  
45 hydrology. While these NASA programs fund research activities that address individual aspects  
46 of the global energy and water cycles, they are not specifically designed to generate a

1 coordinated result. The implementation concept for NEWS is specifically intended to work  
2 across these programmatic boundaries.

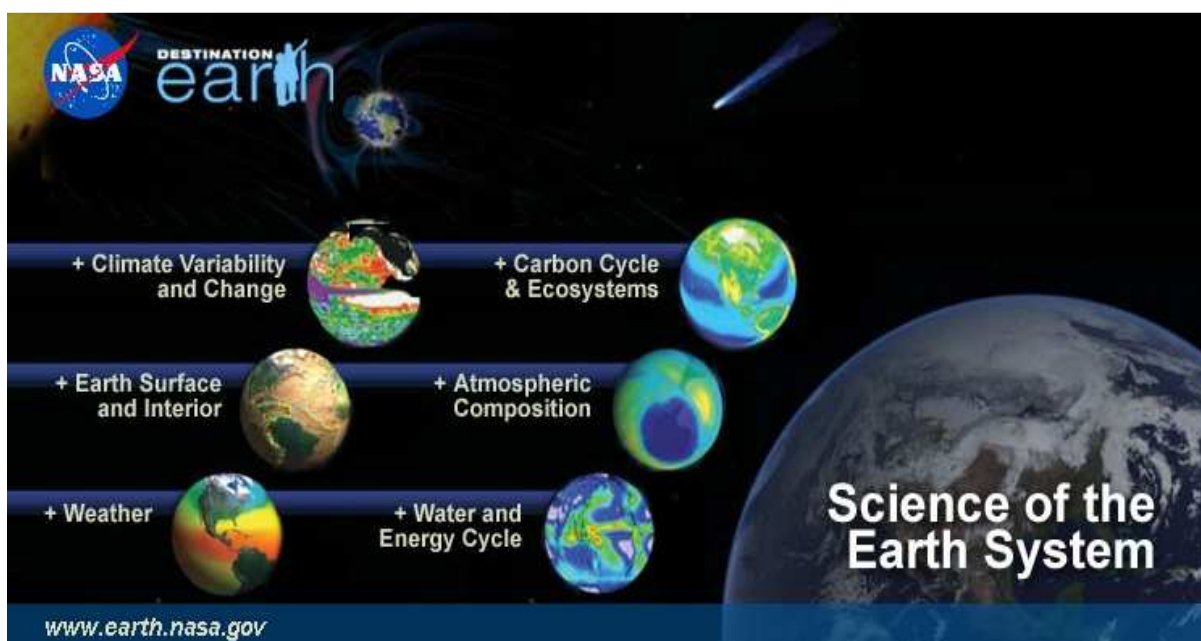
3 The NEWS activity will be comprised principally of product-driven investigations, exploration-  
4 driven investigations and integrative efforts studies. NEWS will include:

- 5 • Product-Driven Investigations: **Systematic research investigations intended to combine**  
6 **and interpret past and current observations, derive global analysis and prediction tools**  
7 **and products and identify technological and observational requirements to guide future**  
8 **NASA investments.**
- 9 • Discovery-Driven Investigations: **Fundamental investigations to identify key missing**  
10 **elements and explore new scientific frontiers topic to improve capabilities and**  
11 **knowledge of the energy and water components of the Earth system..**
- 12 • NEWS Science Integration Team: **Integration of the science activities to serve the overall**  
13 **purpose of NASA by acting as an interface with other ESE research foci and activities,**  
14 **coordinating the conduct of NEWS investigations, and leading specific studies needed**  
15 **for integration of the results of independent product-driven or discovery-driven**  
16 **investigations.**

17 Exchanges of energy and water within the Earth system involve a multiplicity of interactive  
18 processes. Understanding and predicting these processes require a complex multi-disciplinary  
19 research program, innovative observing tools, and advanced model developments. Organizing  
20 these complex activities calls for dedicated management and oversight approaches to ensure that  
21 both financial and human resources are efficiently applied to serve NASA Earth Science  
22 priorities.

# 1 Program Overview

The NASA Earth Science Enterprise (ESE) mission is to understand and protect our home planet by using our view from space to study the Earth system and improve predictions of Earth system change. The ESE, working with its domestic and international partners, provides accurate, objective scientific data and analyses to advance our understanding of Earth system processes and to help policy makers and citizens achieve both economic growth and effective stewardship of Earth's resources. The ESE research program aims to acquire deeper scientific understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life. These interactions occur on a continuum of temporal and spatial scales ranging from short-term weather to long-term climate and motions of the solid Earth, and from local and regional to global scale.



*Figure 1.0: The Water and Energy Cycle is one of six focus areas that define the scientific content of the NASA Earth Science program*

Three research thrusts represent the frontier of current knowledge, for example: (1) explore interactions among the major components of the Earth system – continents, oceans, atmosphere, ice, and life, (2) distinguish natural from human-induced causes of change, and (3) understand and predict the consequences of change. NASA has established six research focus areas for the study of these complex processes (Figure 1.0). These focus areas are: Atmospheric Composition, Carbon Cycle and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather. This implementation plan establishes a methodology to help ESE answer, either in full or in part, the Enterprise's second-tier research questions related to the Water and Energy Cycle focus area: The questions are:

- How are global precipitation, evaporation and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?



- What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?
- What are the consequences of climate change and increased human activities for coastal regions?
- How can weather forecast duration and reliability be improved?
- How can predictions of climate variability and change be improved?
- How will water cycle dynamics change in the future?

The overarching long-term challenge of the ESE Water and Energy Cycle focus area is summarized as: *documenting and enabling improved, observation-based predictions of the water and energy cycle consequences of Earth system variability and change*. The roadmap (Figure 1.1) for this research focus area provides the conceptual framework for research that will be organized and implemented by the *NASA Energy and Water cycle Study (NEWS)*. This and other ESE research focus areas are interrelated and must be integrated eventually to construct a fully interactive representation of the Earth system.

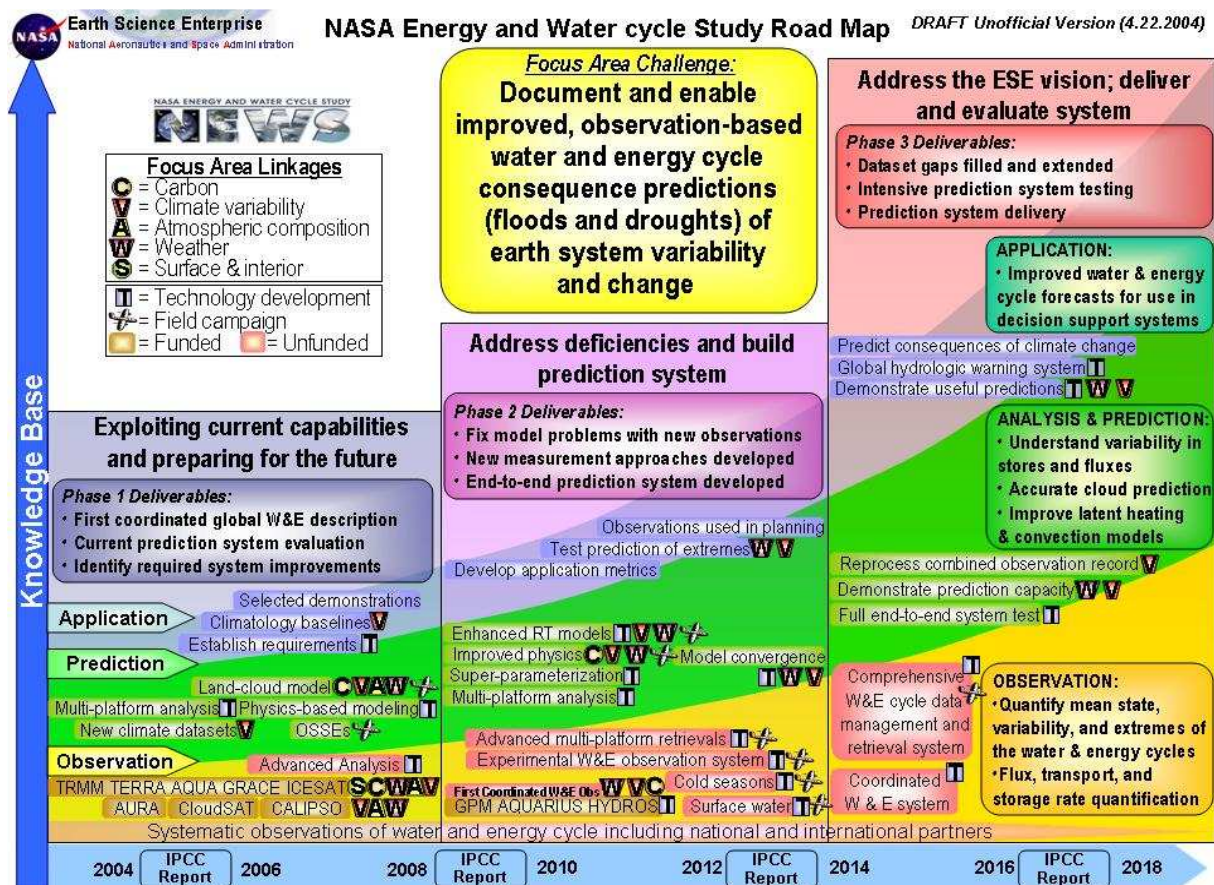


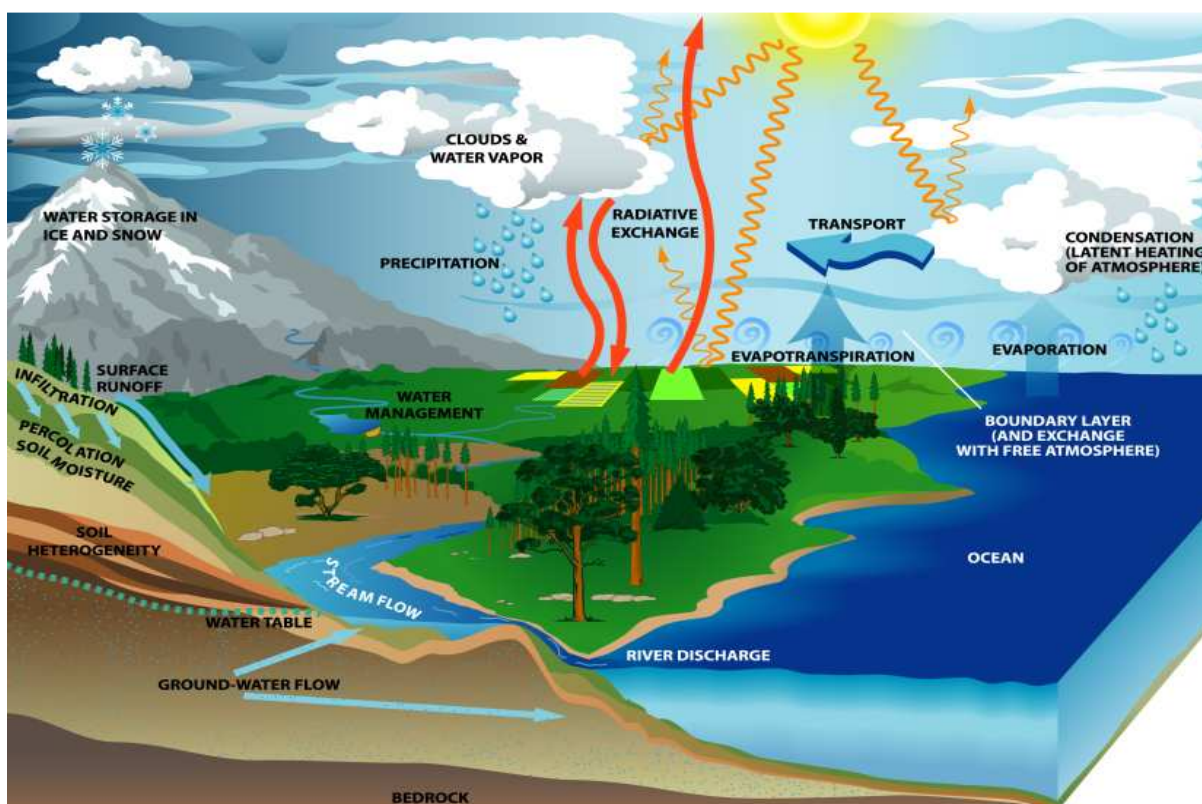
Figure 1.1: NASA Energy and Water cycle Study Road Map

1 This implementation plan also responds to the national scientific priorities identified by the US  
2 Climate Change Science Program (CCSP), encompassing the Climate Change Research  
3 Initiative (CCRI) and the US Global Change Research Program (USGCRP), and to international  
4 scientific priorities identified by the World Climate Research Programme (WCRP), the  
5 Committee on Earth Observation Satellites (CEOS), the Global Climate Observing System  
6 (GCOS), the Integrated Global Observing Strategy (IGOS) and the framework and  
7 implementation plan for the creation of a Global Earth Observing System of Systems (GEOSS)  
8 following the first Earth Observation Summit held July 2003 in Washington D.C. and successive  
9 summits in Tokyo and Brussels in 2004. The goal of these programs is to lay the scientific basis  
10 for the development of public policy and natural resource management tools related to climate  
11 change.

## 12 *1.1 Scientific Scope*

13 The Earth's unique capability to sustain life is due to the abundance and vigorous cycling of  
14 water through the global environment. The global water cycle consists in the transport and  
15 transformation of water within the Earth system, and the distribution of fresh water over the  
16 Earth's surface. This cycling occurs on a wide spectrum of time and space scales, from cloud  
17 microphysics to global redistribution. The water cycle also represents exchanges of large  
18 amounts of energy, as water undergoes thermodynamic phase changes and long-range transport  
19 from one part of the Earth system to another. Because both the radiative effects of cloudiness and  
20 the release of latent heat are intimately linked to weather system dynamics and water  
21 condensation processes, the study of the energy cycle is inescapably entwined with the study of  
22 the water cycle. While the global water cycle drives the hydrologic consequences of climate  
23 changes, it is both a consequence and a driving factor of the global energy cycle.





*Figure 1.2: Conceptualization of the Energy and Water Cycle*

Natural and human-induced changes to the energy and water cycle have major consequences for industry, agriculture, and other human activities. The increased density and exposure of human settlements in flood plains and coastal regions amplify the potential loss of life, property, and commodities that are at risk from intense precipitation events. However, current projections of such impacts will remain speculative until scientific understanding of climate change is validated against observed events and assimilated into reliable global predictions and effective decision support tools applicable to local conditions. Predicting the hydrologic consequences of global change - whether natural or human-induced - and developing practical applications of climate, weather, and hydrologic forecasts are the ultimate challenges of NEWS and the ESE Research Strategy in general.

## ***1.2 Overarching NEWS Goals and Research Priorities***

One of the most important manifestations of change in the Earth's climate would be change in the global water cycle including regional precipitation regimes, increased evaporation and the exacerbation of extreme hydrologic events, such as floods and droughts. From an overall Earth Science perspective, the key questions are whether the expected climate changes (e.g. warming) entail changes in the rate of the Earth's water cycle and what trend may be expected in the future.

While climate research, in general, aims to understand climate processes and predict changes in the state of the climate system, NEWS will investigate temperature/moisture gradients and localized energy/water sources or sinks (flux divergence) that drive weather dynamics, global water transport and hydrologic extremes. It is envisioned that accurate estimations of key energy and water reservoirs and fluxes, including space-time variability and extreme events, will lead to

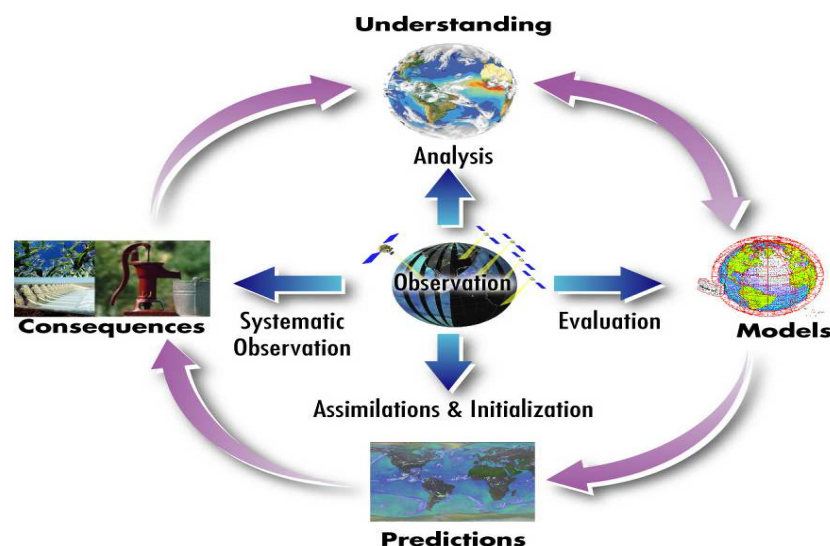
more accurate model representations of energy and water processes and thereby contribute essential new tools for the advancement of climate change science and predictions.

The ultimate goal of NEWS is a breakthrough improvement in the nation's energy and water cycle prediction capability. NEWS is expected to demonstrate advanced global observation, data assimilation, improved representation of physical processes in climate model and better prediction systems that can be used to quantify the hydrologic consequences of climate change and produce useful seasonal and longer-range hydrologic predictions based on observed initial values and changing boundary conditions.

### 1.3 NASA Guidelines

The guidelines for the implementation of the NASA Energy and Water cycle Study result from NASA's overall mission and unique capabilities. The following considerations apply:

- The NASA Earth Science Enterprise addresses energy and water cycle science issues that are *global in scope*. Predictions of energy and water cycle consequences of climate variability and change require understanding global-scale teleconnections and feedback processes. NASA supports related basic research, especially process-resolving modeling or laboratory studies, and invests in field campaigns, but only as a means to enhance the scientific investigations of global phenomena identified by space-based observation.
- NASA currently has substantial energy and water cycle data archives and assets that need to be *integrated* and reanalyzed to make new scientific advances. In addition, NASA maintains a substantial investment in discovery-driven scientific research as well as the development of related technological innovations.
- NASA is a research-and-development agency. While its mission includes supporting research that can enable improvements in operational monitoring, prediction and water resources management, NASA does not itself manage water systems, nor provide operational inputs to such applications. Nonetheless, it is envisioned that NASA efforts will contribute towards national goals for water cycle prediction; especially in developing, testing, and implementing the means to exploit new environmental information delivered by NASA's research programs.
- NASA's unique vocation is to produce key scientific inputs using global observations from space and to exploit these data for Earth system monitoring and for the initialization and validation of global environmental predictions (Figure 1.3). NASA has the capability to support the full range of investigations, from global-remote sensing to point-scale field observations, global data acquisition, and the development of prediction systems that can assimilate these measurements. However, NASA alone cannot achieve the ultimate goal of operational predictions and applications and seeks collaborations with other agencies, the scientific community-at-large and private industry.



**Figure 1.3: NASA's End to End Research Strategy**

Given these premises, this implementation plan describes the anticipated activities, from the acquisition and analysis of global observations to data assimilation and model development that will yield new understanding of the global energy and water cycles, leading to improved prediction systems and innovative applications to water management.

#### **1.4 Implementation Overview**

Consistent with the ambitious NEWS challenge and ESE objectives, the timetable for the implementation of NEWS extends over a 15- year period. During this period, NEWS participants are expected to collect, analyze and interpret observational data from archived records and on-going observing systems, contribute to the preparation of new space-flight missions, advance predictive models of the global energy and water cycle, and lay the foundation for future developments (including potential new observing techniques). NEWS participants are also expected to examine and test new application practices in partnership with relevant operational agencies and industry.

The implementation of NEWS is planned in three phases as described in Chapter 4, each successive phase being focused on a range of research activities previously described in Chapter 3. It is envisioned that NEWS will build upon existing NASA-supported basic research in atmospheric physics and dynamics, climate modeling, and terrestrial hydrology. While these NASA programs fund research activities that address individual aspects of the global energy and water cycle, they are not designed to generate a coordinated result nor synergistic cooperation between NASA scientists and the scientific community at large. The implementation concept for NEWS is specifically intended to work across these programmatic boundaries.

The cycling of energy and water has obvious and significant implications for the health and prosperity of society. NEWS is envisioned to be part of the broader NASA end-to-end Earth science program. The overall program thus includes the transition of research findings and new capabilities to academic/public education and to practical applications, through partnerships with the academic community-at-large, federal agencies that oversee environmental protection and operational applications, and eventually private sector operators.



While the NEWS research program is expected to yield incremental advances and breakthroughs over an extended period of time, progress in achieving its long-term objectives will be measured against its success in making significant contributions to:

- Development and deployment of an experimental integrated energy and water cycle global observing system
- Documenting the global energy and water cycle through obtaining a complete observational record of all associated geophysical parameters
- Building a fully interactive global climate model that encompasses the process-level forcings on and feedbacks within the global energy and water cycle
- Creating a global **land and atmosphere** data assimilation system for energy and water variables
- Assessing the variability of the global energy and water cycle on time scales ranging from seasonal to decadal, and space scales ranging from regional to continental to global
- Supporting the application of climate prediction capabilities for estimating the impact of climate variability and climate changes on water resources **over a variety of spatial and temporal scales**

The breadth of these challenges demands international, multi-agency contributions. As detailed in section 5.0 NEWS will partner and contribute as appropriate to facilitate and enable these advances.

### *1.5 Scientific Organization and Oversight*

NASA investments in Earth science research have resulted in the acquisition of global observation capabilities, data resources, and scientific expertise that must now be integrated to address the NEWS challenges. To this effect, the NEWS activity will be comprised principally of NEWS discovery-driven investigations, product-driven investigations, and integration studies, but it will also be open to any relevant energy and water cycle investigation. NEWS will include:

- Product-Driven Investigations: Systematic research investigations intended to combine and interpret past and current observations, derive global analysis and prediction tools and products and identify technological and observational requirements to guide future NASA investments.
- Discovery-Driven Investigations: Fundamental investigations to identify key missing elements and explore new scientific frontiers topic to improve capabilities and knowledge of the energy and water components of the Earth system.
- NEWS Science Integration Team: Integration of the science activities to serve the overall purpose of NASA by acting as an interface with other ESE research foci and activities, coordinating the conduct of NEWS investigations, and leading specific studies needed for integration of the results of independent product-driven or discovery-driven investigations.

### *1.6 Planning Flexibility*

As progress is made and lessons are learned, it is envisioned that NEWS results will be widely available and evaluated by the scientific community. The NEWS science integration team will periodically review and revise the NEWS implementation plan in the light of the broad community response to the scientific outcome of NEWS.

## 2 Current Capabilities and Development Objectives

### 2.1 Current Observational Resources, Capabilities and Examples of Deficiencies

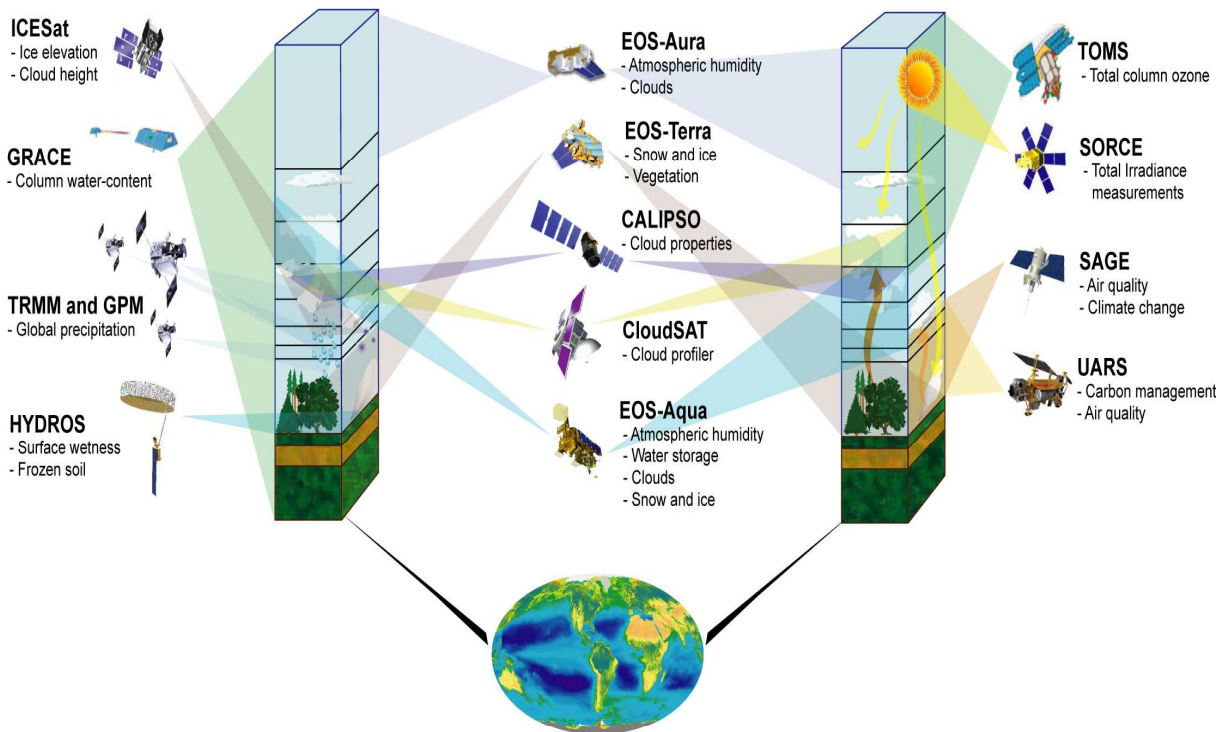
Over the last decade satellites have proven the capability to accurately monitor many aspects of the total Earth system on a global scale. This is a capability unmatched by surface based systems which are generally limited to land areas covering only about 30% of the planetary surface and concentrated in the northern hemisphere. Currently, satellite systems monitor the evolution and impacts of the El Nino, weather phenomena (particularly clouds and precipitation), natural hazards and extreme events such as floods and droughts, vegetation cycles, the ozone hole, solar fluctuations, changes in snow cover, sea ice and ice sheets, ocean surface temperatures and biological activity, coastal zones and algae blooms, deforestation, forest fires, urban development, volcanic activity, tectonic plate motions, and others. These observations are used extensively in real-time decision making and for strategic planning and management of industrial, economic, and natural resources. Examples include weather and climate forecasting, agriculture, transportation, energy and water resources management, urban planning, forestry, fisheries, and early warning systems for natural disasters and human health impacts. Among the most significant outstanding gaps are global observations of land surface hydrology parameters such as soil moisture and ground water storage, soil freezing and thawing, surface water reservoirs and river discharge. Also needed are surface-based, and in-situ observations for determining geophysical variables that cannot directly be measured from space and for the calibration and validation of long-term records of satellite-derived geophysical, chemical and biological quantities.

Historically, operational space-based observations were disparate, not well-calibrated nor uniformly processed, and do not lend themselves to assembling a consistent long-term record of global scale phenomena. Several recent efforts have been directed at re-processing long-term records of operational satellite data using new retrieval algorithms developed by space research. Examples include the derivation of time series of precipitation estimates by applying TRMM retrieval algorithms to historical SSM/I microwave observations.

## Water Cycle Missions

## Water and Energy Cycle Missions

## Energy Cycle Missions



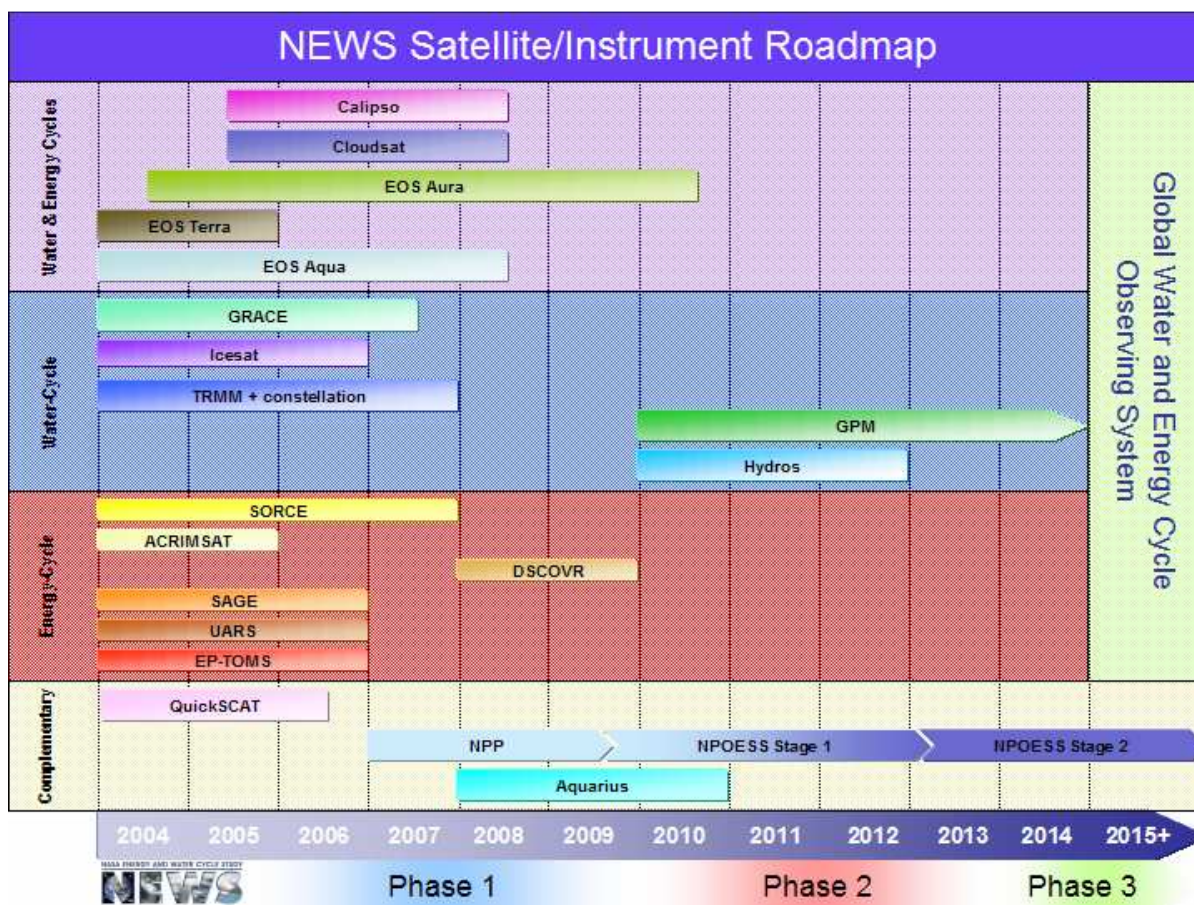
## Complementary Water and Energy Cycle Missions



**Figure 2.1: Satellite Missions to Observe the Global Energy and Water Cycle**

In terms of the more recent, current and pending missions (Figure 2.1), the orbiting fleet of eighteen NASA research satellites providing relevant energy and water-cycle observations include: the TRMM precipitation measurement satellite and the Global Precipitation Measurement (GPM) constellation; the EOS Terra, Aqua and Aura satellites that pave the way to the next-generation NPOESS operational satellites; the GRACE Earth gravity measurement mission; the ICESat global topography mission; Landsat and EO-1 Earth surface imaging; QuikSCAT ocean surface wind measurements; CloudSAT and Calipso to measure the horizontal and vertical structure of cloud, snowfall and aerosol optical properties; SORCE satellite to observe solar radiation, and the other relevant energy and water-cycle missions (i.e. TOPEX-POSIDEON, JASON, QuikSCAT, EO-1, NPOESS, GOES, Aquarius, etc.) further illustrated in Figure 2.2, and detailed on the NASA/ESE website ([www.earth.nasa.gov](http://www.earth.nasa.gov)).





**Figure 2.2: Timeline of Energy and Water Cycle Observations from Satellite Missions**

These experimental/research satellites are typically aimed at measuring specific components and/or processes of the global energy and water cycles, over a relatively short period of time – in a climatological perspective. While measurement systems scheduled for the near future will fill in critical observational gaps or improve current observational capabilities, only incomplete provisions are being made for high quality measurements of some essential climate variables; notably ocean surface winds. This may require collecting data from an ad-hoc succession of diverse satellite measurements and appropriate data analysis methods to ensure long-term consistency. Inferring reliable climatological records of variables and trends in the global energy and water cycle from multiple space and surface based observing systems remains a research challenge, even for basic quantities such as rainfall. Thus, a substantial long-term effort is required to periodically reanalyze the complete collection of satellite data with improved retrieval algorithms, and to develop the means for satellite sensor inter-calibrations. A recent WCRP Report on Satellites Observations calls for the following action: “Space agencies should consider an international effort in order to meet the GCOS and WCRP needs for cross-calibration, overlap, and continuity for operational satellites. Meeting these objectives within budgetary constraints will likely require innovative approaches. Such approaches may wish to consider a cooperative mission using a subset of common passive frequencies in the visible, infrared, and microwave spectrum and optimum orbital configuration to serve as a common radiance transfer standard.”

## 2.2 Current Modeling Resources, Predictive Capabilities and Examples of Deficiencies

The energy and water cycles in nature are interdependent and consist of multiple, highly non-linear, complex physical and dynamical processes (and component systems) that interact with each other continually (radiation transfer, sensible/latent heat and momentum fluxes) or intermittently (precipitation). Current state-of-the-art global prediction systems necessarily consist of simplified representations of these natural processes (processes not explicitly resolved by a model are usually parameterized in terms of explicit model variables). In particular global models run at a nominal grid resolution of about 100 km, and regional and mesoscale models approach 10 km or less, but most energy and water processes actually occur on much smaller scales. How accurately these sub-grid scale processes are represented in global models is an issue. Moreover, the temporal and spatial gradients of key dynamic, thermodynamic or physical fields are vastly different in the atmosphere, over the land surface and in the ocean. Surface temperature, for example is much more spatially homogeneous than precipitation. The energy containing eddies in the ocean are of much smaller spatial scale but longer lasting than those of the atmosphere. Soil moisture gradients frequently are sharp, as they reflect variations in soil type, porosity and conductivity as well as precipitation.

Because of the vast range of significant scales, it is a challenge to adequately represent interactions of the Earth system that involve energy and water exchanges in a uniform way. Even within the terrestrial branch of the water cycle, one must embrace a large range of time scales from minutes/hours for cloud formation, precipitation, evaporation and evapotranspiration, to days/months for ground water flow, to seasons/years for ground water storage. In global coupled models, the simulation and prediction of hydrological cycle quantities (precipitation, soil moisture, water storage) are particularly error prone, compared to temperature. Several diagnostic studies indicate problems with the representation of the atmospheric boundary layer, moisture and moisture convergence, and land surface/hydrology parameterization. Differences in the parameterizations of these components or processes within a model, or between models, lead to disagreement in large scale atmospheric circulation and thermodynamics. Uncertain or unknown parameterization of cloud formation processes (including aerosol interactions) lead to impacts on precipitation as well as radiation feedback, all leading to regional (particularly) and global variances in model-computed water resources. Most current models are suited for estimating first-order changes in atmospheric temperature profiles, (and thus surface temperature) in response to changes in radiant energy transfer or radiative forcing caused by various factors, such as changes in the concentration of greenhouse gases, anthropogenic aerosols, surface albedo, or the solar constant. Assessments of climate change, notably those conducted by the Intergovernmental panel on Climate Change (IPCC), focus almost exclusively on surface and air temperature variations and trends. Existing climate models are notoriously challenged with regards to reproducing and predicting changes in atmospheric wet processes. For example, model development must lead to a reliable capability to prescribe the extent to which variations in the global climate induce predictable changes in the frequency, intensity, and geographical distribution of weather systems.

Over recent years, improved computational capacity, and better observing technology, especially satellites, have led to marked advances in model sophistication and prediction skill. Model simulation/prediction exercises demonstrate the stochastic/dynamic nature of the atmosphere-land-ocean system needs to be represented by ensemble integrations, either using the same model with different initial conditions, or a suite of models with the same prescribed initial conditions, or a combination of both. The physical processes may also need to be represented in stochastic form. Ensemble integrations are routinely performed for weather forecasting. They

are also being introduced in hydrological forecasting of river flow and water resources. To a degree "ensemble" integrations are also applied implicitly in climate change projections based on the results of different participating centers around the world. Recent studies also indicate that even on "weather" time scales, atmosphere-land surface-vegetation-ocean coupled models produce significant improvements. For example, an index based on the depth of the mixed layer (measurable from ocean surface height via satellites) was a better prognostic measure than Sea Surface Temperature (SST) for hurricane development, intensity and track.

For predictions on the seasonal to interannual time scales "super-ensemble" prediction techniques hold considerable promise as "super-parameterization." The former (super-ensemble) evaluates the performance of each model within a suite of models (e.g., those used for AMIP and CMIP intercomparison studies) for regional prediction skills (e.g., precipitation) by comparison to observations (typically re-analysis fields and various precipitation and other products). These so-called training runs over certain specified time periods (based on the available observational time series available) are used to compute spatially differentiated "weights" for the individual model predictions. These weights are then used in the forward prediction integration of the same suite/ensemble of models. The results obtained have been impressive. The latter (super-parameterization) provides a measure of feedback between sub-grid-scale processes (via high resolution cloud models run at a sub-sampled spatial scale) to a global model of lower space/time resolution. Results have been quite promising. In the near term the above two methodologies appear to be the best avenues to improve seasonal to interannual prediction skills. It is to be noted that "superparameterization has not been tested for seasonal-interannual prediction, but the concept conceivably applies to this time scale as well. They could be applied to coupled climate models as well for climate change projections not yet tested. On the longer term, the fundamentals of global models (be they atmospheric or coupled) need to be improved (dynamics, physics, parameterizations etc.). This, the latter activity, is a considerably more challenging task. It includes a better understanding of microphysical processes via observational experiments and modeling studies, one which NEWS will begin to address, alongside efforts to improve prediction skills of water/energy cycle parameters on the short term in order to facilitate the delivery of applications products for water resource management (as an example) among others.

There is a trend towards increasing model resolution to better capture sub-grid scale processes such as cloud formation and precipitation. Increased resolution is also used to better represent topographic features and atmospheric circulation in the vicinity of mountains in order to improve local predictions of orographically induced convection. Of course, a better resolution of even large mountain ranges has a pronounced effect on the atmospheric circulation dynamics. Regional models are run at approximately 50 or 80 km resolution (some are down to about 12 km) while global models are at resolutions ranging (typically) between 100 and 500 km, typically. However, increasing spatial resolutions beyond 1-10 km (as needed to resolve processes that were parameterized in larger scale models) requires taking into account non-hydrostatic effects associated with vertical transport as well as sound and gravity waves, among others. Several theoretical assumptions (regarding process parameterizations) that were/are applied to the larger-scale resolutions need to be re-designed or discarded. Increasing horizontal resolution also has a direct impact on the time resolution needed to avoid computational instabilities, and on the vertical resolution needed to effectively represent the atmospheric stratification.

Thus, implementing high resolution models within a theoretically consistent framework has a large impact on the computational resources required to carry out a model integration.



1 Currently, high resolution is attempted only in sub-regional to meso-scale models. These models  
2 are run in "embedded" mode, namely: they require boundary conditions derived from a larger  
3 domain regional or global model. The spatial extent of a high-resolution, non-hydrostatic model  
4 will constrain the maximum forward integration time the model is capable of executing before  
5 boundary errors will cascade to the interior of the high-resolution model rendering its forecast  
6 meaningless. Currently, down-scaling and up-scaling (parameterization) problems are not fully  
7 resolved, and will take a serious research effort before adequate resolution. Terrestrial  
8 hydrological models are typically designed to run on a catchment or basin scale. Linking these  
9 models with atmospheric models integrated at much larger scales continues to pose problems.  
10 Atmospheric and hydrological models possess widely differing levels of complexity which  
11 attempt to partition the surface rainfall input (observed or modeled) into runoff, infiltration,  
12 percolation, etc. Some include lateral transport of water. Some employ one-dimensional water  
13 budget accounting schemes, while others incorporate complex dynamics and lateral coupling.  
14 They all require surface observations or model derived inputs for flux computations and  
15 initialization. Improvements, therefore, in hydrological model predictions, on any time scale,  
16 depend upon considerably better observations of the atmosphere-land-vegetation interface and  
17 the representation of these processes in models. The closure of terrestrial energy and water  
18 budgets on any space/time scale continues to be a problem. Thus, in summary:

- 19 • Models hold considerable promise for full environmental prediction, but the limits to such  
20 prediction have yet to be fully established. Furthermore, collecting the data necessary to  
21 evaluate model results presents its own challenges. Models produce numerous fields of  
22 physical variables, all of which could or should be evaluated against observations. But, most  
23 often, uncertainties resulting from either model deficiencies or observational data cannot be  
24 resolved. To address these problems, it is customary to carry out focused field campaigns or  
25 field experiments with enhanced observations over limited domains to research one or more  
26 process or hypothesis. Except at the most basic stage of model formulation, such space and  
27 time limited intensive field studies cannot be generalized, either because they do not define  
28 mean field and boundary conditions completely enough or because the models to be  
29 evaluated cannot ingest the information. Thus, there is a concurrent need for accurate long  
30 time series of observational fields and for model simulation/prediction experiments aimed at  
31 improving the representation (parameterization) or simulation (prediction) on time scales  
32 ranging from hours/days (hazard warnings) to week and months/seasons (for resource  
33 management), or longer (for determining the impacts of global climate change).
- 34 • Although a wealth of satellite data has become available in recent years, not all climate  
35 models are positioned to use it, due to the simplicity of the parameterizations employed  
36 and/or because the data must still be transformed into geophysical quantities that are  
37 appropriate for the model. Data assimilation systems are largely designed to use these data,  
38 but data assimilation presents its own challenges. Furthermore, model error propagation,  
39 needed for assigning assimilation weights, is not quantitatively known. The overall  
40 implication is that both our observed and theoretical bases of climate predictability are still in  
41 question.
- 42 • Finally, a central scientific challenge for NEWS will be to improve the fidelity of sub-grid  
43 scale, parameterized processes in coupled regional and global models so that physical  
44 feedbacks in the climate system are adequately represented. Indeed, the notion that these  
45 energy and water processes can be parameterized to the extent needed remains an open  
46 question-one that NEWS will necessarily confront.

## 2.3 Current Application and Consequence Capabilities and Deficiencies

Applications of energy and water cycle research are extensive in scope, yet few of the methodologies can said to be mature. Short-term weather and flood forecasting (hazard warning) and hydrologic predictions for water resource management, including impact of El-Nino/La Nino cycles and global climate change are familiar examples. Early warnings of weather hazards are routinely delivered to mitigate the impact of severe weather on transportation (land and shipping), agriculture, and other application sectors that require decisions to be made on these time scales. The management of water resources on a daily to monthly time period requires water cycle variables to be measured to hourly intervals to support such practices as irrigation management and flood forecasting. Conversely, the management of resources on an annual basis requires the delivery of projections or predictions of water cycle variables on a month to seasonal to inter-annual time scale, for it to be effective or usable. Economic and infrastructure development sectors require the delivery of future predictions/projections of Earth/climate system variations and change on time scales ranging from decades to centuries, in particular, building new infrastructures (e.g., dams, hydro-power etc., agricultural development, land use and urban expansion etc.) requires environmental projections on the long-term time horizon, partly because such projects take 10, 20, or more years to design, build and implement.

Examples of recently developed applications of current scientific understanding include:

- A joint NOAA/NASA GAPP funded project on improving water demand analysis and prediction for water managers is designed to improve the estimates of evapotranspiration over the Middle Rio Grande Basin in New Mexico from just above Cochiti Reservoir southward to Elephant Butte Dam. It uses satellite, radar, surface observations and numerical forecasts with land surface modeling to integrate Land Data Assimilation System information into water operations decision support systems displayed on the web. Reclamation's water managers and their stakeholders in water conservancy districts and farmers may access the information daily to conserve extremely limited resources
- A 51 year (1948-1998) reanalysis of the U.S. land-surface hydrology has been completed by NOAA/NCEP (GEWEX/GCIP/GAPP) using the NOAA land model which is also used in the NOAA/NASA North American Land Data Assimilation System (NLDAS). The VIC, Mosaic and Sacramento models are also incorporated in NLDAS. The reanalysis defines surface climate, including inter annual variability, and places extreme events in a historical context to aid forecast applications at NCEP/CPC.
- A joint NOAA/NASA project on improving water demand analysis and prediction for U.S. Bureau of Reclamation water managers is designed to improve estimates of evapotranspiration (loss of water from the soil) in New Mexico. The project uses satellite remote sensing, radar, and surface-based observations, and numerical forecasts and surface modeling, to integrate Land Data Assimilation System (LDAS) information into water operations decision support systems, and displays decision data on the Web. Bureau of Reclamation water managers, water conservancy districts, and farmers may access the information daily to help them conserve the state's extremely limited water resources.
- An experimental on-line decision support tool designed to provide users with a description of streamflow conditions and their accompanying probabilities in the Pacific Northwest, from near-term climate predictions and long-term projections, is being developed, demonstrated and deployed in the Columbia River Basin. Data assimilation systems and land surface models developed by NASA, NOAA, and other agencies and universities will be integrated

1 with river system management decision support systems developed by the Bureau of  
2 Reclamation and used by water managers to make daily to seasonal water operations  
3 decisions.

4 Water resources applications are limited due to an inadequate measurement of the high temporal  
5 and spatial variability to the various states and fluxes of the water and energy cycle. Typically,  
6 remote sensing with its synoptic and repetitive features is well suited to improve water cycle  
7 measurements. However, satellite sensors must be used to convert or model the electromagnetic  
8 signal (although see novel gravitational approach of GRACE in Section 2.1) to a complex value  
9 of the water and energy cycle states and fluxes, typically associated with a significant error.  
10 Water cycle budget uncertainties are further compounded by the general decline in worldwide  
11 surface measurements. Therefore, there are significant application problems from errors to  
12 measuring most of the various states of the water and energy cycle from both remote sensing and  
13 *in situ* measurements.

14  
15 Clearly, the investment in NEWS along with other national and international activities will  
16 provide significant reductions in the water and energy balance errors where in many regional to  
17 global areas we are not even within 50% of closing the water balance. Significant improvements  
18 will enable water managers and policy makers for improved decisions. For example, there is an  
19 alarming world-wide decline in stream gauges leading to worsening of water and energy budget  
20 errors. This leads to practical problems such as water management practices of planning and  
21 scheduling irrigation practices, flood planning, hydropower use, and fisheries. The proposed  
22 NEWS Surface Water Mission and other activities (e.g., improved precipitation and hydrological  
23 distributed modeling) should improve measurements and compensate for the decline in gauged  
24 basins. Other deficiencies that NEWS work will significantly reduce include the difficulties  
25 associated with estimating soil moisture (i.e., HYDROS) and terrestrial water storage (i.e.,  
26 GRACE and Surface Water Mission), and snowpack amount and distribution (Cold Land  
27 Process Mission). However, the largest uncertainty to the water budget will be addressed by  
28 GPM that will provide significant improvements in spatial and temporal resolution of  
29 precipitation processes. Currently, regional to global precipitation errors are significant  
30 depending on the location (e.g.'s mountains, coastal areas, oceanic, etc.) and process (e.g.'s,  
31 coastal, snowfall, mountainous, etc.). Another water and energy flux difficult to measure via  
32 remote sensing is evapotranspiration or latent heat flux. Typically, latent heat flux (or  
33 evapotranspiration) is solved as a residual to the energy balance or directly with numerous  
34 assumptions. As indicated above, the error in closing the water budget from all of the  
35 uncertainties over various temporal and spatial scales often exceeds the amount to make  
36 intelligent water management decisions. A high goal of NEWS is to reduce the errors through  
37 remote sensing and modeling that are associated with water flux measurements from regional to  
38 global areas that will provide the quality measurements useful for many water resources  
39 applications. See Section 3.3 for possible application benefits from NEWS.



### 3 Key Energy and Water Cycle Research Challenges

The Earth's energy and water cycle is driven by a multiplicity of complex processes and interactions, many of which are poorly understood. Its characterization requires an understanding of moisture and energy exchanges among the Earth's atmosphere, ocean and land, and biological systems over a wide range of space and time scales. The difficulty is exacerbated by the fact that water can exist on Earth in any of its three phases. NEWS planning is focused on selected aspects of the energy and water cycle that reflect the science and technology interests and capabilities of NASA. The following sections briefly outline the key components and tools that will be emphasized by NEWS research.

#### 3.1 Key Components of the Global Energy and Water Cycle

##### 3.1.1 Cloud, Radiation, and Precipitation Processes

It can be argued that the transport and condensation of water vapor are at the core of global atmospheric dynamics and climate change. Indeed the greenhouse effect of water vapor by far dominates the other components of the earth radiation balance. The maximum water-carrying capacity of the atmosphere is constrained by the Clausius-Clapeyron relationship but a crucial additional factor is the effect of atmospheric dynamics and physics that maintains the global mean relative humidity around 75% at the surface. Given an effectively infinite source of water at the ocean surface, it is likely that weather-induced atmospheric motions (that bring moist air parcels to saturation) and condensation processes control the amount and cycling rate of water in the planetary atmosphere.

Weather systems and indeed the general circulation itself are fueled by radiant energy and latent heat released by the condensation of atmospheric water vapor. Both the extent and optical properties of water and ice clouds (which control radiation fluxes) and precipitation are governed by cloud system dynamics and microphysics. Because cloud processes occur on characteristic scales of micrometers to kilometers - much smaller than the scales usually resolved by general circulation and even mesoscale models - climate models so far have not accounted for cloud processes in a realistic manner. Deficient representation of cloud amount and optical properties is generally recognized as the principal cause of error in model computations of energy and water fluxes, and a major source of uncertainty in climate model projections.

Advancing the knowledge of cloud systems and the role of clouds in global climate poses major scientific and technical challenges. Improved microphysical models are required to address the formation and growth of cloud particles in diverse saturated environments produced by atmospheric motions. This problem is especially acute for ice phase clouds. Important related issues to be considered include the role of aerosols as condensation nuclei and cloud particle freezing-melting processes. The goal of NEWS is to develop and exploit comprehensive Process-Resolving Cloud System Models, or in short Cloud-Resolving Models (CRM), that explicitly represent the fundamental dynamical and microphysical processes (such as the indirect effect of aerosols on cloud particle growth) that determine precipitation rates and radiation fluxes. Elements of this task are:

- Formulating effective CRM codes and incorporating essential features into climate models.
- Acquiring suitably detailed and comprehensive observations of cloud structure and optical properties, radiation fluxes, precipitation, atmospheric circulation parameters, and aerosols

for testing CRM and global climate model representations. With the deployment of the "A-train" satellite constellation and future GPM missions, NASA is uniquely poised to acquire the full range of data required to address this problem.

- Developing and implementing the analysis and/or data assimilation schemes needed to reconcile model results with observations.
- The implementation plan calls for an intensive research effort to develop new model computations of radiant energy, heat and water fluxes that resolve, at least partially, the characteristic scales of cloud process dynamics. (See sections 4.2.3 Modeling and 4.2.1 Observations).

### **3.1.4 Indirect Radiative Effect of Aerosols**

As discussed in the Climate Change 2001 report (IPCC, 2001), anthropogenic aerosols have a direct impact on climate by increasing both the scattering and absorption of solar radiation. In addition, aerosols act as cloud condensation nuclei and affect cloud microphysics, thus inducing indirect effects by modifying cloud properties and their effects on the planetary radiation budget and precipitation. The level of understanding of these phenomena is very low, while the potential magnitude of indirect forcing by aerosols is quite significant (IPCC, 2001). This indirect aerosol forcing links both the energy and water cycles, and is an appropriate element of the energy and water cycle crosscutting program. On the other hand, direct aerosol forcing is more appropriately covered by the Atmospheric Chemistry and Composition Focus area and the Radiation Sciences Program (RSP). (See section 5.1.4)

There are several key steps to isolate the indirect effect of aerosols that must be addressed in this program:

Aerosol effects on clouds must be separated from the effects of atmospheric dynamics. This requires sorting of a very large collection of observations and model simulations according to the synoptic situation.

- Aerosol chemical composition is generally unknown, but at least an approximate knowledge of the aerosol source region constrains this uncertainty (e.g. industrial origin, desert dust, forest biomass burning, grassland/agricultural burning, etc.). To make effective use of this information, improvements are needed in aerosol and atmospheric data assimilation, chemical transport models, and aerosol physics and chemistry simulations.
- Observations must establish that the aerosols and the cloud layer under consideration are co-located (same vertical layer, at the same time and same geographic location). This will typically require combined lidar, radar and radiometer profile data for cloud and aerosol vertical layering, as well as effective assimilation of aerosol data and source region information).
- Investigating a large number of cases is required to cover the range of cloud types and statistically reduce noise from weather phenomena that dynamically affect cloud properties. Extensive global cloud, aerosol, and weather information will be required for this purpose.
- Cloud Resolving Models (CRM) and Large Eddy Simulations (LES) dealing explicitly with cloud dynamics and microphysical properties in various (bin-resolved) size and composition categories will also be needed to complete the diagnostics and lead the way to global climate impact assessments.

The first opportunity to effectively address the aforementioned issues will come with global data sets provided by the A-Train satellite constellation (CALIPSO and CloudSAT launch in Spring 2005) analyzed in combination with observations from heavily instrumented surface sites like those maintained by the DOE ARM project. In the near term, the implementation plan calls for exploiting new global observations and high resolution models. The NASA Radiation Sciences program and the DOE ARM program will be expected to support relevant field measurements addressing outstanding aerosol chemistry issues, and the absorption by black carbon.

### **3.1.3 Ocean Fluxes and Atmospheric Transport**

The top of atmosphere (TOA) and the interface with continents and oceans are the two main boundaries between the atmosphere and its environments. Fluxes of energy and water through these two interfaces drive the general circulation and atmospheric transport of heat and water. The response of the hydrological cycle to rising concentrations of greenhouse gases is an important source of uncertainty for predicting future changes to Earth's climate and composition. The small amounts of water vapor in the upper troposphere (UT) exert high leverage in Earth's radiative balance. Of particular concern is moisture in subtropical regions. Measurements of H<sub>2</sub>O in the upper troposphere (UT) will provide important new insights into how moisture is supplied to the subtropical middle and upper troposphere.

At the ocean-atmosphere interface, on-going data analysis projects already produce world-wide estimates of radiant energy and of latent heat (water vapor) fluxes, inferred (mainly) from satellite-based remote sensing of ocean surface temperature and winds, atmospheric temperature and humidity profiles, aerosol distribution, and cloud optical properties. Still both estimates are based on incomplete observational information (e.g. no air temperature or moisture data near the surface) and therefore rely on empirical approximations that are, by their very nature, difficult to validate under different climatic regimes. Thus, considerable room exists for further improvements in air-sea flux estimates, notably by exploiting new and more informative global retrievals of vertical temperature and moisture profiles reaching into the lower troposphere (AIRS, etc.), and of cloud/aerosol particle distribution and planetary boundary layer height (CloudSAT, CALIPSO, ICESat, TRMM and GPM).

Another approach uses global assimilation of a wide variety of meteorological data into general circulation models. While such 4DDA analyses do reproduce transient weather patterns with considerable realism, flux estimates derived from model-based analyses or re-analyses are not reliable (mainly because of the flux increments that result from the initial adjustment of the model atmosphere to the assimilation of new data and the lack of appropriate physical constraints). Advances in model representations of atmospheric turbulence, boundary layer dynamics, and general model physics would help minimize these artifacts.

Furthermore, it is unlikely that any satellite-based remote sensing system would deliver wind profiling measurements with the sampling density and precision required for determining directly both the rotational and divergent components of the atmospheric wind field in the foreseeable future (10-15 years), although key information on surface winds over oceans is available. Absent direct measurements of wind, estimates of sensible and latent heat (water vapor) transport by the atmospheric circulation will continue to be compromised by systematic model errors, especially faulty representations of the radiant energy and latent heat sources that drive atmospheric flow divergence. Thus, closing the energy and water budgets on the atmospheric side will remain an outstanding problem for some time.



On the other hand, the (relatively) slowly changing ocean storage and transport of heat and fresh water provides another view of the global and regional energy and water budgets on the oceanic side. Baroclinic weather systems, precipitation patterns, and indeed the global water cycle are governed by latitudinal temperature gradients that result from net solar radiation, ocean poleward heat transport and storage. Observations of the oceanic heat and fresh water storage and transport (especially, Aquarius and various *in situ* measurements) under the ESE Climate Variability and Change research focus area (see section 5.1.1) are directly applicable to determining energy and water budgets at the surface of the ocean, and constraining flux estimates based on atmospheric data. Conversely, changes in the deep ocean circulation are thought to be primarily sensitive to changes in river discharge into the North Atlantic reducing the density of surface water and the rate of North Atlantic deep water formation. This is recognized as a major scientific issue in the NEWS science plan and climate change research in general, including international activities supported by CLIVAR and CLiC.

To address these problems, the implementation plan calls for more accurate analyses of atmospheric and oceanic data, and coherent multivariate estimates of radiant energy, sensible heat, and latent heat fluxes or flux divergence, using consistent single-column and 3-dimensional models of relevant dynamical and physical processes and both atmospheric and ocean data assimilation.

### 3.1.2 Land Hydrologic Processes

Evapotranspiration is the principal active link between land and atmosphere in the energy and water cycle. Additionally, runoff - and its progression into river/reservoir systems - is crucial to water-resource management and hydrologic predictions. Advances in remote sensing during the past decade, the development of land models capable of simulating hydrologic, geophysical and biogeochemical processes, and data assimilation techniques have led to considerable progress in the ability to compute water fluxes over the vast range of land classes that span the globe. However, substantial uncertainty remains as to the veracity of these land surface models and their application to practical hydrologic forecasting.

A measure of this uncertainty is the substantial differences that these complex computational schemes still exhibit in their estimates of global hydrologic fluxes and our inability to conclusively verify or constrain these model simulations. At the current stage, it is equally important to minimize uncertainties in all three aspects of the problem: model representations of the diversity of soil properties and hydrologic processes, quality and/or fidelity of observations, and assimilation techniques for merging disparate data sets. The implementation plan calls for:

- Formulating single-column and 3-dimensional process models that explicitly or statistically resolve all critical spatial scales and simulate all governing processes which couple the land hydrology to the atmospheric boundary layer and general circulation.
- Developing more capable coupled land and atmosphere data assimilation systems based on the above advanced models, to exploit the full range of observations from existing and planned satellite missions (Figure 2.1) and other relevant datasets.
- Assembling sufficient site-specific field data sets and global observations to test the range of parameters characterized by the advanced models above.
- Seeking improvements in pedologic, geologic and vegetation data sets that are required fixed inputs for land modeling.

- Determining the scientific merit and investigating the technical feasibility of potential innovative approaches for global measurement of crucial hydrologic variables such as evapotranspiration of land surface and water discharge from major river basins, etc.

Knowledge of the storage of water, over land regions, is vital to predicting the longer-term variations and trends in the global water, energy, and carbon cycles. Key reservoirs include: soil moisture, soil freeze-thaw conditions, snow and ice cover, groundwater, and inland water bodies such as lakes and rivers. Despite the importance of these storage terms, the fact remains that no long-term, global-scale measurements are available. Remote sensing from space now has the potential to effectively quantify these water storage terms.

In this context, the implementation plan calls for exploring and developing the means to extract water storage information from available or potential new remote sensing data, specifically:

- Validate retrieval algorithms and data products against *in situ* field and airborne observations
- Explore the feasibility of innovative satellite observing techniques for global detection of changes in hydrologic quantities such as water storage.
- Assimilate water-storage retrievals into appropriate hydrologic prediction systems to assess their consistency and impact on prediction skill.
- Quantify the expected predictive impact of pending experimental or pathfinder missions, (i.e. ESSP), consistent with anticipated accuracy and sampling density.

In addition to this effort to upgrade current data retrieval and analysis, it is considered equally important to revisit and improve historical datasets. The implementation plan calls for reprocessing legacy data sets with the latest retrieval algorithms to merge with newly acquired information and produce consistent extended time series, for the purpose of assessing the significance (predictability) of historical extreme events and trends.

## **3.2 Key Tools for Energy and Water Cycle Research**

### **3.2.1 Advanced Radiative Transfer Methods**

Satellite remote sensing requires inverting the radiative transfer equation to retrieve geophysical quantities of interest. In view of the sensitivity of retrieval products to even small changes in outgoing radiation, the inversion (retrieval) process must be based on the best possible radiative transfer model(s) that cover all wavelengths from UV to microwave, discriminate polarizations in incoherent and coherent radiation, and accommodate both passive and active sensing techniques. To support the development of advanced satellite retrievals, radiation transfer models must have physically consistent representations of atmospheric composition, cloud ice and water particles, hydrometeors and precipitation, surface roughness, and vegetation or soil properties across the whole electromagnetic spectrum. Models should specify each component in terms of physical variables (even if values have to be assumed) instead of empirical relationships, and aggregate detailed scattering and emission parameters on satellite footprint scales. Further advances in fundamental quantum physics and spectroscopy may be required to accurately model continuum absorption and emission of gases.

Radiation transfer codes that fully satisfy these requirements do not currently exist. The development of more accurate radiation transfer models is the fundamental underpinning of any major new advance in satellite remote sensing. The implementation plan calls for the development of a new generation of radiation transfer codes for remote sensing applications. The

radiative transfer processes for wavelengths from UV to microwave for irregularly shaped objects and uncommon size distributions, and in complex inhomogeneous media, such as ice and snow particles and snow packs, grass and tree leaves and vegetation canopies, and soils, are major difficulties of radiation calculations, and must be investigated deeply.

Most current retrieval techniques exploit only a few selected wavelengths from a single satellite instrument, and therefore do not provide either the best analysis of the available satellite data nor total physical consistency across data products. New, faster retrieval techniques (e.g. adjoint model equations or statistical-inverse models) must be developed, that are general enough to allow the simultaneous retrieval of a range of geophysical quantities from multiple wavelength, multiple sensor and multiple platform measurements. Such methods must be based on rigorous forward models of the measured radiation. The implementation plan calls for the development of advanced multi-variate retrieval methods that can exploit the totality of the spectral information acquired by Aqua and the "A-train" satellite constellation, and eventually analyze data from the whole energy and water cycle observing system. The development of more powerful radiative transfer codes and multi-variate retrieval methods is a prerequisite for acquiring crucial information for the success of NEWS.

### **3.2.2 Advanced Global Observations**

Global observations of energy and water cycle variables are actually needed for three quite different purposes. First, long term records of significant climate and hydrologic indicators are used to characterize the variability and explore the predictability of the global energy and water cycle, based on observed characteristic time scales (frequency spectrum) and apparent responses to quasi-instantaneous disturbances. Second, comprehensive observations of (ideally) all aspects of the complex processes involved in the global energy and water cycle are required to explore the interactions between these processes and conduct penetrating tests of their numerical representations. Finally, complete observation-based determinations of relevant state parameters are needed (ideally) to initialize model predictions. It is expected that observation requirements for process studies and energy and water cycle predictions will be further refined in the course of NEWS implementation.

While many important hydrologic processes can be characterized from *in situ* measurements only, satellite observations are essential to embrace the global energy and water cycle, which involves the global atmospheric dynamics and global fluxes over land and oceans. Satellite remote sensing provides really extensive information about Earth system variables where *in situ* measurements are sparse (e.g. over oceans, remote polar regions, or mountainous terrain).

The implementation plan calls for a specific effort to maintain critical global climatological records of essential atmospheric and hydrologic indicators. The calibration and independent verification of these records are critical for long-term energy and water cycle monitoring and modeling studies. The implementation plan also calls for systematic investments in scientific and conceptual studies and technological developments to further improve both measurement techniques and information retrieval methods relevant to the global energy and water cycle.

#### ***3.2.2.1 Climate and Hydrological Change Indicators***

The principal indicators of variability or trends in the global energy and water cycle and land hydrology are radiant energy fluxes at the top-of-the-atmosphere (TOA) and surface, surface temperature, atmospheric temperature and humidity, global precipitation (ideally both liquid and solid), and river discharge. Surface temperature, atmospheric state variables, and TOA radiation



will likely continue to be adequately monitored by existing and planned meteorological space- and surface-based observing systems, particularly EOS Terra and Aqua, NPP, the NPOESS program, and European METOP satellite series.

The estimation of tropical global precipitation is the focus of the TRMM and GPM missions respectively. Before the launch of TRMM and during a potential gap between TRMM and GPM, the international GEWEX Global Precipitation Climatology Project (GPCP) produces a coherent (though possibly biased) long-term record of global rainfall. GPCP is based on merging information from operational observing systems (infrared radiometry from geostationary meteorological satellites, microwave radiometry from DMSP and NPOESS, and land-based rain gauge networks). However, there is also a need for higher time-resolution measurements of precipitation: GPM is a major first step, but the more extreme precipitation events have time scales less than 3 hours. The technology for precipitation measurement from geostationary orbit needs to be developed.

Accurate river stage or discharge data are most readily obtainable, in principle, from stream gauging stations around the world. Unfortunately, not all important river basins are adequately gauged, nor are stream flow data generally available, certainly not in near real-time. On account of existing difficulties in the international exchange of hydrologic data, global satellite-based observation of river discharge and stage of inland water bodies must be considered. Several types of experimental altimeter and possible Doppler radar or lidar systems are being envisaged for this purpose (Surface Water Working Group).

#### ***3.2.2.2 Hydrologic and Atmospheric Process Observations***

A great deal more observation-based information is needed to study and successfully model the physical, chemical, and biogeochemical processes that contribute to the global cycling of energy and water. Additional data are needed to understand hydrologic and atmospheric processes, construct and test stand-alone and coupled numerical representations of the processes, and measure progress achieved in predictive performance of advanced climate models. Additional data requirements include global observation of 3-D cloud system structure, ice particle and water droplet distributions within clouds, cloud optical properties, rain drop distribution and inferred rainfall, boundary layer height and vertical structure, soil hydraulic properties and surface wetness, evapotranspiration, and high-resolution information on vegetation type, water content, and aerodynamic roughness.

Process-oriented field studies and high-precision systematic measurements at experimental stations or sites are crucial data sources for basic energy and water cycle studies, but do not usually cover the whole range of hydrologic and meteorological regimes. Global sampling provided by NASA research satellite missions and other advanced remote sensing systems are crucial to complement systematic measurements and penetrate the basic physical, chemical, and biogeochemical processes that underpin the energy and water cycle. Important new observing tools that support NEWS process studies include EOS Terra and Aqua, forthcoming CloudSAT and CALIPSO and GPM satellites, prospective HYDROS and Aquarius missions, the European ENVISAT and SMOS missions, and potential new sensors.

#### ***3.2.2.3 Initial Value Data***

With the exception of deep aquifers, energy and water cycle processes in the atmosphere and over land span a range of characteristic time scales from hours to several months or seasons. Thus, progress in *developing* the capability to predict changes in the energy and water cycle can

be validated by comparing deterministic weather forecasts and/or seasonal to inter-annual climate predictions against a large enough number of independent observed variations. For this (regional) purpose, it is convenient to uncouple the regional energy and water cycle dynamics from the full climate system, and initialize regional atmospheric and land hydrologic variables only. Thus, the principal additional data requirements for NEWS (beyond numerical weather prediction requirements) are initial values of land water storage, i.e. soil moisture, snow, inland water bodies, and/or the total mass of ground water. Energy storage in the ocean is also a necessary initial condition for long-time-scale predictions.

Several approaches are or will shortly be tested, including methods to infer soil moisture, vegetation water content, atmosphere-land interaction, and snow water equivalent from combined satellite microwave, visible and infrared data (using both passive and active sensors on DMSP, Aqua, HYDROS, and SMOS), satellite altimetry of river cross-sections and inland water bodies (potential "surface water" survey mission), and the recovery of transient variations in the Earth gravity field associated with changes in total water mass (GRACE). Currently, this new "photon-less" remote sensing method can detect changes in mass distribution equivalent to a 1cm slab of water spread over 1000x1000 km<sup>2</sup> and may eventually reach twice that resolution (NRC, 1997). However, none of above methods has delivered fully satisfactory information so far, either singly or in combination.

An outstanding problem is continent-scale observation of critical cold weather hydrologic quantities: solid precipitation, water equivalent of snow on the ground, frozen or thawed state of the ground. Seasonal snow cover and glaciers store large amounts of fresh water. Seasonal and permanent soil freezing severely reduces the infiltration, storage and migration of ground water. The influence of seasonal and permanent freezing further extends to vegetation phenology and carbon fluxes, cold region engineering, trafficability, and a variety cold land hazards.

### **3.2.3 Coupled Assimilation**

Data assimilation is an objective method to estimate the state of the earth system from irregularly distributed observations. These methods integrate observations into numerical prediction models to develop physically consistent estimates that more completely describe the Earth system state than the raw observations alone. This process is the fundamental paradigm for providing initial conditions for Earth system prediction, and for increasing our understanding and parameterization of Earth system behavior through various diagnostic research studies. Data assimilation has great potential to advance the understanding and prediction of the global energy and water cycles by combining large amounts of heterogeneous land, ocean, and atmosphere observational data into a coherent whole. Data assimilation is especially valuable in isolating systematic errors and biases in satellite observations, and for assessing the impact of future satellite observations.

An important goal of the NASA energy and water cycle study is to develop coupled interactive earth system models that link the atmosphere, oceans, land masses, and biosphere into a comprehensive whole. Model-assimilated data sets provide an improved description of much of the global system and its interacting components, and can be invaluable for addressing the major NEWS challenge of tracking global and regional variability in the energy and water cycle. The production and evaluation of analysis of the Earth system are necessary steps in the development of accurate and useful coupled land, ocean and atmosphere data assimilation and prediction systems for the global energy and water cycle. The scales resolved by this analysis must include diurnal to centennial time scales, and individual catchment basins to global spatial scales. The

1 full spectrum of energy and water processes in the system must cover cold and warm season,  
2 high and middle latitude, subtropical, and tropical regions, and atmosphere, land and ocean from  
3 the subsurface to the top of the stratosphere. To enable application to water resources,  
4 streamflow, soil moisture, evaporation and precipitation must be realistically represented.

5 Most current data assimilation efforts utilize separate, uncoupled (i.e. inconsistent) atmosphere,  
6 ocean and land data assimilations. These systems generally do not maximize information  
7 extracted from the growing suite of remote sensing measurements. Further, energy and water  
8 cycles are not adequately described by current model analysis systems, with analysis increments  
9 resulting in important non-physical contributions to the global energy and water budgets.  
10 Analysis errors are often the sum of large compensating errors in individual processes, including  
11 precipitation, and surface and atmospheric fluxes.

12 While truly coupled assimilations will be needed eventually to improve coupled predictions, the  
13 current separate land-ocean-atmosphere data assimilation methodology currently provide a better  
14 description of the global energy and water cycles due to inadequate understanding of feedbacks  
15 between the complex subsystems. For example, current uncoupled Land Data Assimilation  
16 Systems (LDAS) use observed precipitation and solar radiation as forcings (not true coupled  
17 assimilation), to avoid cloud and precipitation errors that are characteristic of coupled systems.  
18 It is precisely these fluxes or energy and mass exchanges that are at the heart of Earth system  
19 feedbacks and which, at present, are so uncertain in coupled models. To achieve the goal of  
20 fully coupled atmosphere-land data assimilation systems that should produce the best and most  
21 physically consistent estimates of the energy and water cycle NEWS will need advanced coupled  
22 process models with improved feedback processes, better observations, and comprehensive  
23 methods for coupled assimilation.

24 The elements of this effort are as follows:

- 25 • Identify and obtain all relevant observations of precipitation, snow, soil moisture, upper  
26 atmosphere humidity, evaporation, and other components of the energy and water cycle,  
27 implement an integrated, multicenter, nationally focused archive system for these  
28 observations, and model-assimilated and-tested data sets and provide for ready access to  
29 these data sets by the scientific community over the long term.
- 30 • Assess closure of the observed global and regional energy and water budgets over various  
31 timescales to provide benchmarks for model based analysis and prediction methodologies.
- 32 • Develop methods to assimilate measurable components of the energy and water cycles,  
33 including precipitation, cloudiness, radiation, evaporation, temperature, humidity, vegetation,  
34 soil moisture, groundwater, cryosphere, etc.
- 35 • Perform Observing System Simulation/Sensitivity Experiments (OSSEs) to specify the  
36 requirements for new observation systems.
- 37 • Develop more realistic energy and water process models, especially those associated with  
38 convection, clouds, land surface, and boundary layer processes.
- 39 • Compare energy and water processes from different model analyses to better understand  
40 uncertainties, with particular attention paid to spinup, observation evaluation, and the  
41 behavior and role of analysis increments.
- 42 • Develop coupled land-ocean-atmosphere data assimilation systems that achieve internally  
43 consistent, accurate and unbiased estimates of the energy and water cycle.

- Establish graduate education and research opportunities in four-dimensional geophysical data assimilation to provide essential expertise.
- Improve ability of assimilation models to accurately depict regional, zonal, and global trends, which are not handled well in current assimilation products. Run models in a frozen analysis system for climate data applications.

### 3.2.4 Advanced Analysis of Multiple Data Sources

New approaches to the analysis of satellite measurements, data assimilation products, and forecast model outputs are necessary to solidify our understanding of global energy and water cycle variability and trends. The deployment of the Earth Observing System and associated Pathfinder missions (A-train) accentuates the need for new methods to integrate data from multiple sensors and platforms and to extract information from these data on the spatial and temporal characteristics of energy and water cycle processes. Analyses of current data sets will identify gaps that need to be filled to complete a comprehensive global observing capability.

The implementation plan calls for more informative satellite data products generated by merging data from multiple sensors and platforms. Examples are different measurements of a single quantity (e. g, vertical profiles of a quantity in different altitude ranges and total-column amounts) and flux estimates derived from measurements of several parameters. Such products require co-registration of multiple sensor data, possibly from different satellite or sensors, and the application of single-column retrieval algorithms or fully 3-dimensional data assimilation systems for generating physically consistent fields of energy and water cycle quantities. The implementation plan calls for developing optimal techniques to merge disparate data sets, algorithms for assimilating physical data products into atmospheric and surface process models, and estimates of associated error characteristics.

In order to quantify and understand the variability of the energy and water cycles, satellite and model-assimilated data products need to be analyzed in ways that illuminate the spatial and temporal features of the individual component quantities and their interactions over all critical time and space scales. The key satellite data sets must be cross-calibrated between platforms and sensors that overlap in time, making use of *in situ* data as independent standards. Methods for partitioning errors between different noisy datasets will be necessary to correctly identify geophysical signals in the presence of observational error. The implementation plan calls for assembling and maintaining, with minimal spatial and temporal gaps, consistently calibrated, long-term, global data sets such as radiation balance at the top-of-the-atmosphere, atmospheric temperature and humidity, cloud climatology, surface-radiation budget, precipitation climatology, etc.

Comparison of these enhanced data sets with relevant climate model products, and systematic *in situ* measurements or field campaigns will provide the basis for assessing the performance of retrieval algorithms, the consistency of *in situ* point measurements, and the error characteristics of derived data products. The analysis of field measurements will also support radiative transfer and geophysical process model developments, sensor calibration, and retrieval algorithm developments.

Deficiencies in current observing systems will be identified from the outcome of the above analyses and inferred error characteristics of global datasets, highlighting the critical gaps in observational capabilities of energy and water cycle. These diagnostics will constitute a scientific basis for new technology and mission developments, leading to future flight missions.



Evidence of changing rainfall rates and patterns will be obtained through the integration of measurements from the worldwide network of land-based rain gauges and spaceborne observations, with particular attention to the tropical oceans. Assessing variability requires homogeneous global rainfall information that can only be assembled from a combination of surface-based and space-based measurements.

Global estimates of evaporation will be inferred from multiple satellite data sets. Over the ocean, the feasibility of estimating evaporation from satellite data only has been demonstrated and still needs to be improved with or without combining remotely sensed data with full 4-dimensional assimilation of meteorological data. Over land, a combination of remotely-sensed data, state-of-the-art models explicitly representing dynamical, physical and biogeochemical processes, and data assimilation will be necessary to improve estimates of continental evapotranspiration. The implementation plan calls for estimates of global P – E budgets based upon combined ocean and land evaporation data, global precipitation data, upper-ocean salinity and ground water storage information, for the purpose of identifying regional trends in fresh water fluxes.

Analyses of global observations of cloud, water vapor, and boundary-layer properties, will improve our understanding of precipitation and evaporation (that control the rate of the global water cycle). In general, it is expected that the analysis of changes in water, radiant energy and heat sources and sinks over space and time will lead to direct an estimation of the sensitivity of the Earth's climate system to feedback mechanisms.

Global trends of soil moisture and freeze/thaw state will lead to better understanding of climate change impacts on cycling of water, energy, and carbon at the land surface, and will improve weather and climate predictions. Analysis of snow and ice cover and depth over land will enhance modeling of river basin response, stream flow forecasting, and surface energy balance for climate modeling. New altimetry and gravimetric data will be used to estimate river discharges and deep groundwater storage.

### **3.2.5 Advanced Earth System Modeling**

Computational models of the climate system play a central role in any effort to understand, simulate, and predict variability and changes in the Earth geophysical, chemical, and even ecological environment. Considerable talent and resources are already being invested in the further improvement, validation, and scientific exploitation of climate models. Regarding the global energy and water cycle, however, all model development efforts face two overarching scientific challenges:

- The gap between the scales of atmospheric motion that are explicitly resolved and the scales where cloud, boundary layer, and hydrological processes actually occur.
- The gap between model output quantities and the geophysical variables that can actually be observed and measured in nature. This gap hampers defining climate prediction metrics that account for both natural variability and forced responses.

Microphysical processes, such as condensation of water vapor to solid or liquid state, are governed by local values of temperature, relative humidity, cloud condensation nuclei distribution, etc., but certainly not by the mean values of these quantities over atmospheric slabs 100 x 100 km<sup>2</sup> in size. Obviously, relationships between local parameters do not apply to large or even meso-scale averages. Conversely empirical relationships (known as parametric formulas) that may be found between area-averaged quantities do not reflect verifiable process

physics and are bound to change when cloud-scale local parameters vary. Similar limitations apply to hydrologic processes at the land surface and, to a lesser extent, to planetary boundary layer dynamics (turbulent fluxes) everywhere. Addressing this gap in climate model capabilities is the topic of section 3.2.5.1 below.

Measuring progress in climate models according to objective metrics is the other major problem. Comparisons between model predictions and global (large-scale) climatological data derived from measurements provide necessary but insufficient constraints. First, climate signals may be below the level of natural climate variability (noise). Second, there may be many possible ways to adjust model algorithms so as to match global mean quantities, such as global rainfall, because there are too many feedbacks and forcings to tie down causes and effects unambiguously. A possible complementary approach is validating climate models in numerical weather prediction (NWP) mode, i.e. compare deterministic predictions to observed instantaneous variations. NWP allows a clearer test of individual processes such as clouds and precipitation, moreover it is well known that physics bias in climate models tend to occur early on in the numerical integration, and that they can be better detected during the early stage of the integration, before the large scale effects dominate. However, the NWP approach also has serious (but different) shortcomings. First, weather prediction noise is so large, that subtle climate feedback processes are unlikely to be tested at sufficient accuracy. Second, ocean fluxes and atmospheric feedbacks are uncoupled in NWP, so that critical variables like vertical velocities are poorly determined. A possible approach to overcome NWP shortcomings may be analyzing large ensembles of weather cases grouped by dynamical state such as cloud type or atmospheric state variables, or extending both prediction and verification to seasonal or even interannual time scales. The implementation plan calls for climate model tests over a wider range of time and space scales, and more penetrating analyses beyond the examination of simple grid-box averages (see section 4.2.2).

### ***3.2.5.1 Global Energy and Water Cycle Model Development***

Given the level of on-going efforts devoted to the exploitation and further development of global climate models, the implementation plan calls for the cooperation of interested modeling teams to develop and test potentially revolutionary model formulations that resolve - at least statistically - the characteristic space- and time-scales of atmospheric energy and water processes and explicitly represent relevant basic parameters. Advances in computing technology now make it possible to implement such process-scale resolving representations that have the potential for more closely reproducing the highly non-linear behavior of atmospheric processes and delivering much improved approximations of energy and water fluxes.

### 3.2.5.2 *Cloud, Precipitation and Radiation Processes*

The representation of cloud dynamics and microphysics is a major source of uncertainty in global modeling, which induces serious errors in model computations of radiation transfer and precipitation. Errors in radiation fluxes and flux divergence (radiative heating/cooling) directly impact the accuracy of predicted changes in temperature gradients and weather developments, which in turn control rainfall. Furthermore, cloud processes and properties may respond, through micro-scale physical processes, to changes in "external parameters" such as natural and artificial aerosol distribution or aircraft condensation trails. Further refinements of microphysical models are required to address the formation and growth of cloud particles in the saturated-vapor environment produced by atmospheric motions and the role of aerosols as condensation nuclei.

The ultimate objective from a modeling viewpoint is to develop and implement comprehensive Process-Resolving Cloud System Models, in short Cloud-Resolving Models (CRM) that explicitly represent the principal features of cloud system dynamics and basic microphysical processes (such as the indirect effect of aerosols on cloud particle growth). CRM outputs are comparable to single-column parametric formulations of cloud processes in climate models but, unlike the latter, effectively account for the diversity of cloud systems and cloud properties within resolution elements of general circulation model. The implementation plan calls for exploring alternative methods for estimating radiation fluxes, latent and sensible heat fluxes, and rainfall based on CRM dynamics and microphysics, sampling if necessary the spatial/temporal diversity of cloud systems within a climate model's resolution box.

It is envisioned that CRM will first be verified by comparison with detailed field and space-based measurements from CloudSAT, CALIPSO, and GPM in a variety of selected meteorological situations, and then compared with mesoscale models that reproduce the same meteorological fields, with full or sampled representations of cloud-scale dynamics and physics. Finally, advanced cloud process representations will be incorporated in global climate models to replace simple single-column parameterization schemes and the outcome will be tested against global satellite observations and available field measurements.

### 3.2.5.3 *Land Hydrologic Processes and Evaporation*

Land hydrologic processes are most crucial for determining hydrologic variations and extremes that directly affect human safety and property. Equally important, the varying contrast between continental and marine climates is a controlling factor in the earth climate system, as shown by the seasonal monsoon regimes.

In addition to large-scale atmospheric parameters, spatial and temporal variability in rainfall and surface radiation, combined with land surface heterogeneity, cause complex variations in all processes related to surface hydrology. This variability constitutes a major challenge for climate system models. The characterization and proper model representation of spatial and temporal variations in land hydrologic processes are critical to understanding land surface-atmosphere interactions and resulting climate extremes, especially floods and droughts.

Large errors in surface temperature forecasts can be traced to poor handling of the surface radiation budget, latent heat exchanges associated with evaporation, and soil freezing or thawing. Likewise, snow and frozen ground in late spring appears to have a lasting effect on weather patterns. In this manner, land hydrological processes may induce positive climate feedback that could enhance extremes of drought, or heavy precipitation and flood. Furthermore, snowmelt is a

significant contribution to river flow and can be a major water resource in some mountainous regions. Reliably modeling the partitioning of rainwater and snowmelt among evaporation, ground storage, and run-off is a prerequisite for quantitative application of climate predictions to water resource management.

The principal obstacles hampering progress in land surface hydrology are incomplete observational knowledge of relevant land surface properties at the required spatial resolution over the world's continents, poorly resolved model representations of hydrological processes, and incomplete coupling of land-surface modules with the free atmospheric circulation. It is possible that cloud-resolving models informed with appropriate data will provide an effective framework for developing physics-based representations of land hydrologic and boundary layer processes, and for testing statistical sampling schemes applicable to the estimation of land surface fluxes in global climate models. The implementation plan calls for addressing these deficiencies through better utilization of currently available land surface and water storage data, experimental process models, and comprehensive verification against intensive field measurements, aircraft observations, and large-scale diagnostics based on satellite observations.

#### ***3.2.5.4 Ocean Climate and Marine Boundary Layer***

Latent and sensible heat fluxes from oceans are obviously crucial inputs to the earth climate system. On the relatively short characteristic time-scales of energy and water cycle phenomena, ocean dynamics may be taken as specified. Nonetheless, fast variations in heat and fresh water content occur within the upper ocean mixed layer, in response to changes in air-sea fluxes, rainfall, and solar radiation. The implementation plan calls for improvements in global circulation model representations of marine boundary layer turbulence and upper-ocean mixing, for more reliable atmospheric model computations of heat and water fluxes, and more accurate retrievals of flux quantities from satellite observations.

The new ability to produce seasonal through decadal estimates of global ocean surface radiation, heat, and fresh water fluxes provides the means to close the energy cycle on decadal time scales for the first time. The completion of the deep ocean ARGO float array, together with global satellite-based measurements of ocean surface temperature, salinity and height enables determining the time-dependent upper-boundary conditions and initial oceanic state variables to predict future changes in the world ocean circulation. Global ocean data assimilation products would in effect constrain the integrated effect of diverse ocean mixing processes and help quantify poorly observed phenomena, such as sporadic deep ocean mixing events akin to atmospheric convection.

The implementation plan calls for cooperation with ocean data assimilation experts and finding innovative ways to use global satellite and *in situ* data sets to understand the coupled ocean-atmosphere energy cycle. Improvements in knowledge of fast atmospheric processes, such as cloud effects on energy fluxes and precipitation, are also expected to yield improved predictions of ocean surface boundary conditions. Also required is the cooperation of ocean modelers to exploit new information on ocean vertical mixing processes and improve model predictions of future ocean heat transport and state variables, including sea-surface temperature that strongly influence atmospheric circulation at all time scales.



### 3.2.5.5 Integrated Climate and Water Cycle Model Prediction

The ultimate demonstration of NEWS scientific advances is to be found in the development of a new generation of climate models that account for all significant physical parameters in the climate system and testing decadal or longer model predictions against past and current climatological records. The implementation plan call for integrating NEWS-generated advances in the representation of energy and water processes into consistent GCM frameworks and building a *comprehensive energy and water data assimilation and prediction system* that explicitly predicts the significant (energy containing) space- and time-scales of the energy and water cycle.

### 3.2.5.6 Global Energy and Water Cycle Model Validation

The value of model-based climate predictions hinges on the ability to demonstrate the verisimilitude of model simulations of intrinsic climate variability and climate response to observed disturbances (forcing). A major difficulty stems from the enormous number of degrees of freedom encompassed by the climate system, which makes any holistic verification very difficult. In the past, climate models have been tuned to replicate observed mean states of temperature, radiation, wind, etc. This is widely understood as insufficient; coupled climate system models will have to be verified on a number of levels. There are too many ways to arrive at a particular climate state through adjustments of individual process parameters and not enough known independent events to unravel the complexity of the system and identify a unique cause for each discrepancy. Higher order moments of variability for energy and water fluxes, frequency distributions of state variables, and other objective measures of variability will be needed to assure that the energy and water physics packages produce a realistic climate. Many of the observables discussed in sections 3.2.1 and 3.2.3. will have to be analyzed in similar fashion and used to quantify the realism of the improved prediction system. Listed below are some candidate methodologies.

The implementation plan calls for modeling research proposals that define suitable performance metrics based on the comparison of model products with relevant observations. Potential validation strategies are:

- Off-line testing of individual process modules or combinations of modules (one-way coupling with the atmospheric circulation) by comparing process model outputs with detailed field measurements over selected experimental sites. This method is likely appropriate for testing individual process formulations when necessary boundary conditions can be defined from observations and assimilated in the process model.
- Testing global model products in a deterministic NWP mode over a large number of independent weather events, using observed initial values and transient boundary conditions as appropriate. This method is likely appropriate for evaluating, over short to intermediate time periods (days to a week), model computations of fast processes closely linked to, or driven by weather dynamics, e.g. the life cycle of cloud systems, rainfall, flash floods, etc. The implementation plan calls for the participation of climate modeling teams who can invest in the development of appropriate data assimilation procedures and process diagnostics, and/or the participation of weather prediction teams who can upgrade the formulation of physical process to match the performance of climate models.
- Testing ensembles of climate model predictions over a number of test cases of seasonal to interannual changes or anomalies in the atmospheric circulation and hydrologic regimes.

This method is likely suitable for testing model simulations of phenomena with longer characteristic time scales, such as atmospheric circulation blocks, changes in water storage, extended flooding events, or long-standing anomalies in the upper-ocean heat and fresh water content. The implementation plan calls for investing in the development and exploitation of expanded data assimilation and "spin-up" techniques for initializing the relevant model parameters in addition to conventional atmospheric variables (e.g. soil moisture, snow mass).

- Testing ensembles of decadal or longer term climate and hydrologic prediction by comparing to past and current climatological records. More penetrating tests of integrated model formulations of climate dynamics and thermodynamics may be possible by comparing computed second-order quantities, such as fluxes or energy conversion rates, with statistics derived from the whole range of global measurements. The implementation plan calls for the development and maintenance of these diagnostic tools and long-term global climatological data sets.

### **3.2.6. Technical Studies and Key Technology Requirements**

NASA's Earth Science Enterprise (ESE) conducts a technology program that develops advanced technical capabilities for future ESE science and applications systems. Advanced technologies provide the foundation for a new generation of sensors, instruments, information systems, and high-end modeling frameworks. When infused into mission systems, new technologies yield improvements in our ability to observe, process, and disseminate data and information products to ESE customers. The Earth Science Technology Office (ESTO) is responsible for development of a comprehensive technology-investment portfolio that meets ESE's science focus area needs identified in the science road maps.

For the Water and Energy Cycle focus area, ESTO will address the technologies (instrument, information systems, and computational) needed for river discharge rate, river stage height, global soil moisture, and snow water equivalent.

#### **3.2.6.1 Instrument Technologies**

Present spaceborne instruments only measure the moisture of the uppermost layer of soil, and there are significant limitations on the type of ground cover that can be present for measurements to be made. An instrument that could sense the soil moisture at root zone depth (1 to 5 m below the surface) would offer a tremendous advance in our ability to make meaningful measurements of global soil moisture, leading to a vastly improved ability to understand and model hydrological processes. A VHF/UHF/L-band SAR could yield high payoff here, since it is the only existing instrument concept for measuring soil moisture at root zone depth. (That is different from the concept of inferring the existence of water under the Earth's surface using gravity missions such as GRACE). Soil moisture at the surface can be measured with the same type of instruments used for measuring sea surface salinity. These include: 1) 25m real-aperture conically scanning L-band radiometer, 2) a 25m 2-D L-band STAR system, and 3) a 25 x 50m torus with pushbroom scanning.

Snow is a very important aspect of the water and energy cycle. For measuring snow water equivalent and snow wetness, the development of three technologies is recommended (no ordering implied). The first is a C- and Ku-band polarimetric SAR. The second is a 6 m conically scanning K- and Ka-band passive radiometer. This would be similar to existing instruments, except for the factor of 3 larger antenna, which would require new technology. The third is a 6 m K- and Ka-band STAR. One of these technologies, or better yet, a

passive/active combination, would then serve as the future observing capability for snow water equivalent and snow wetness.

The freeze/thaw transition of the land surface and the length of the growing season is an important aspect of the water and energy cycle. The development of 3 technologies is recommended. First, the Ku-band SAR described in the above paragraph can also be used for measuring the freeze/thaw transition. Second, the Ku- and C-band SAR described in the above paragraph can also measure freeze/thaw transition. The third is a 25 m L-band Synthetic Thinned Aperture Radiometer (STAR) described for soil moisture measurement.

Global precipitation is obviously a very important aspect of the water and energy cycle. To make continuous measurements of atmospheric temperature, water vapor, and rainfall, a scanning microwave sounder in geosynchronous orbit can be used. A 4m aperture scanning radiometer is recommended for GEO operating in the 50 and 183 GHz bands. A STAR operating at 50 and 183 GHz should be considered as an alternative to mechanically scanned antenna. Also, the dual-frequency (14/35-GHz) precipitation radar option will allow coverage of light and heavy rainfall and snowfall. The other recommended instrument is an X- and Ka-band STAR, in which recurring per unit costs have been reduced, in order to enable a constellation to be flown, in order to realize short revisit times. Temporal resolution is extremely important to the measurement of precipitation, since it is so variable in time.

It is not currently possible to measure river stage height and discharge rate from space. This important aspect of the water and energy cycle is part of the link between the hydrological cycle and ocean circulation. The recommended instrument is a Ka-band InSAR operating in a cross-track mode. This initial proof-of-concept instrument could lead to an important ability to monitor the world's rivers on a routine basis, to improve the understanding, and ultimately the modeling, of the links between water on the land and in the oceans. Surface elevations, including ground topography, vegetation height and vertical structure, and river and lake stage can be measured using a photon-counting imaging lidar with sensor wavelength of 532nm. Also, scanning laser altimeter at 1064nm can provide landscape-scale (10km swath), high resolution (10m pixels), and 3-dimensional mapping of the earth's surface (vegetation and surface topography).

### 3.2.6.2 Information Technologies

- *Onboard Storage Architecture:* Instruments having greater precision and resolution will require increased on-board storage capacity in which to store instrument data prior to its transmission to the ground. New storage technologies will be essential in the implementation of the sensor web. Volumetric/Optical memory devices are projected to have a memory density of 0.2 bits/mm<sup>3</sup> with an access rate of 2 Gigabits/sec.
- *Microprocessor, Board and Buss Technology:* These component technologies are critical elements in implementing an effective on-board processing capability. They are all related to speed, flexibility and adaptability of the data collection, processing and transmission capability of the sensor system. Radiation-tolerant and radiation-hardened processing devices will improve central processor reliability in the presence of radiation-induced errors. Buss speeds are one of the notable bottlenecks in processing. Optical buss technology will provide a revolutionary increase in the rate at which data can be moved between processors, memory and peripherals. Processors that can execute 1 billion instructions per second will enable essential on-board processing functions needed to support the data manipulation requirements of sensor webs.

- 1 • *Lossless & Lossy Data Compression:* Data compression when combined with feature  
2 identification, compression can significantly increase the quantity of useful scientific data  
3 collected in a time interval. Lossless data compression has mathematical limits on  
4 compression ratio. Lossless compression rates at 220 millions of samples per second and  
5 with a 5:1 Compression Ratio approach these limits of performance capability. Lossy data  
6 compression is highly dependent upon the data source and upon the perception of the user.
- 7 • *High Data Rate Communications:* Current EOS systems employ X-band radio frequency  
8 technology, operating in the 7.25 – 8.4 GHz frequency band. X-band systems have been the  
9 mainstay of NASA high data rate (75 -150 Mbps) communications, but have limited  
10 available bandwidth to serve the increasing demand for throughput over the next decade.  
11 Future systems will need the wider available bandwidths provided in the 17.3 – 31 GHz  
12 frequency band which can transmit at 300 – 600 Mbps rate. Because of the much smaller  
13 size constraint of Ka-band hardware, this technology may also be suitable for use in satellite-  
14 to-satellite communication applications, which could provide support for networked satellite  
15 constellations. Optical communications technologies represent a breakthrough in terms of  
16 available bandwidth. Increases in data rate (~Gbps) could be several orders of magnitude  
17 over radiofrequency (RF) technology. Satellite to satellite communications will almost  
18 certainly require this technology.
- 19 • *High-Performance Evolvable Archives:* With multi- and hyperspectral data streaming in  
20 daily, the storage and archiving of Earth science data has become a new challenge. Tera- and  
21 petabyte storage media have become a necessity not only in the Earth science regime, but the  
22 entire digital world. Current File Storage Management Systems (FSMS) are primarily  
23 company proprietary products such as UniTree, AMASS, and FileServ. The ANSI/AIIM  
24 MS66 standard of 1999, Metadata for Interchange of Files on Sequential Storage Media  
25 Between File Storage Management Systems (FSMS), provides for a standard tape format,  
26 including file-level metadata. Future archives will require development of a database  
27 management system (DBMS) that accommodates swath geolocation data and evolvable  
28 storage media and formats including storage, archival, and retrieval standards. Advanced  
29 intelligent archives are also needed for knowledge discovery, extraction, and extrapolation.
- 30 • *Intelligent Platform & Sensor Control:* Autonomy will be an essential part of platform  
31 control. Intelligent systems will control the sensor web and integrate the platform with  
32 sensor measurement requirements. The projected intelligent platform technologies described  
33 here will enable a greater number of satellites to be controlled within the sensor web. The  
34 first generation capability will enable autonomous control and formation flying within a  
35 limited constellation of satellites and develop concepts for larger sized sensor webs. The  
36 second generation of autonomous control architectures will incorporate new software  
37 paradigms and algorithms in order to control a greater number of satellites. Agent-based  
38 reference architecture for multiple autonomous spacecraft (~50) is an essential capability for  
39 autonomous control of large numbers of formation flying satellites.

### 40 **3.2.6.3 Computational Technologies**

- 41 • *Cloud Resolving Global Models:* The requirement for developing a cloud resolving climate  
42 model at 1 km resolution so that the precipitation cycle can be accurately modeled implies a  
43 substantial increase in computing capability and modeling technology. The technology  
44 requirements exceed those (by several orders of magnitude) for climate seasonal-to-  
45 interannual prediction at 25 km, which have been analyzed in detail in the *Report from the*  
46 *Earth Science Enterprise Computational Technology Requirements Workshop, 2002*. Model  
47 throughput in the range of 100 Teraflops to several Petaflops will be required, which demand



technology advances in computing architectures and in numerical algorithms for modeling cloud physics. Continued evolution of the Earth System Modeling Framework to enable hydrology modeling components to couple to state of the art climate models with cloud resolving physics components will be necessary to allow the water cycle community to leverage the modeling advances of the climate community. The complexity of developing, validating, and managing the execution of coupled models at this scale (which assimilate observational data from a variety of sensors) will require new programming environments as described in the workshop report.

### **3.3 Key Application Benefits from NEWS**

The primary goal of the NASA Global Water and Energy Cycle activity is to enable improved predictions of energy and water cycle consequences from Earth system variability and change. A critical component forthcoming from NEWS will be to assess and predict changes to the water cycle at various spatial (regional to global) and temporal (days to decadal) scales. Due to the crosscutting nature of water in the Earth System there is a broad range of applications that can benefit from improved understanding and prediction of the global energy and water cycle. Many of the goals of NEWS parallel the goals of the Earth Observation Summit Framework and the application objectives described in the 10-year implementation plan from the ad hoc Group on Earth Observations. Efforts in NEWS are towards developing the full potential for applications. Clearly, there is a goal of NEWS to closely tie together “science-applications-technology”. Moreover, the development of energy and water cycle global data sets and predictions will lead to an improved system benefiting both poor and rich nations. This will especially assist developing nations with inadequate quantitative observations thereby helping equalize the current widespread differences between countries.

#### **3.3.1 Weather and Climate.**

The improved knowledge and predictions from these activities on regional weather and climate will provide information to meet the challenges confronting our society. Short-term heavy precipitation events from hurricanes and severe storms cause the highest monetary impact from natural disasters. NEWS will help lead an improved understanding and prediction of the integrated water cycle providing important information to reduce the effects from floods/heavy rainfall. Improving the short-term to seasonal prediction of floods will also permit water managers to determine optimal allocations for hydroelectric or agriculture usages. In addition, the amount and extent of snow in the water cycle, an important objective of NEWS, is also critical for flood prediction. The improved short-term prediction of water cycle events (<10 days) may cause dramatic improvements in early warning flood prevention, preparedness systems and flood assessment and relief management. Improved weather forecasts allow city managers to more accurately purchase energy contracts. If the accuracy of 30-hour weather forecasts improves 1°F, the annual cost of electricity can decrease by over \$1 billion.

Being able to provide improved seasonal to interannual predictions to the global energy and water cycle will provide numerous ways for better resources management. A better prediction of the scarcity or abundance of precipitation will affect for example water managers determining the allotment of water for agriculture, hydropower, fisheries, and flood control potentially saving potentially billions of dollars. With improved short term precipitation forecasts (e.g., 10-90 days), water resources managers may reduce (or increase) reservoir water amounts while potentially reducing the disastrous consequences from possible future heavy precipitation

causing flooding, or on the other side, providing increase water flow for meeting societal (e.g., agriculture) and environmental (e.g., fisheries) needs.

Another crucial area is the ability to predict seasonal to interannual drought. The prediction of areas undergoing periods of drought may provide advanced warning to help mobilize and prepare to better deal with water shortages potentially saving large numbers of human life. Associated economic impacts to global crop production from drought are significant. More accurate predictability of those events may aid commodity price planning, agriculture water use management, and soil loss/stabilization management. Improved surface parameterization from incorporating land surface information such as soil moisture will significantly improve their predictive capability.

Many models suggest that due to anthropogenic changes there is an intensification of the water cycle leading to increased precipitation and evaporation yielding an increase in extreme events of floods and drought. A key question is to assess and predict by how much and where the water cycle is accelerating with possible links to anthropogenic versus natural induced variations. Natural variability of water and energy fluxes associated with shifts in the Pacific Decadal Oscillation, North Atlantic Oscillation, or other low frequency phenomena are likely to dominate decadal variability in the near term. Distinguishing these signals from anthropogenic effects (increases to greenhouse gases and aerosols, land use changes) is critical for providing scientific input to policy makers. It is changes to the water cycle, more so than changes to temperature that directly affect societal needs. However, current climate modeling research work is much further along with predicted changes to temperature than precipitation. The study of the integrated energy and water cycle system with an understanding and prediction of how components of the system interact will lead to better decision making for issues such as seasonal flooding, droughts and water supply. The NEWS will provide enhanced understanding of the effects from various human induced changes from burning of fossil fuels, land cover change, and emission of aerosols to changes to the water cycle. It is the quantification and prediction of these actions to the water and energy cycle that is of high importance.

### **3.3.2 Summary of application benefits from NEWS**

In the previous section benefits associated from weather and climate were summarized. Clearly, due to integrative and pervasive nature of water study there are numerous benefits that may be discussed. A summary of some of the important application benefits from the implementation of NEWS in addition to Weather and Climate are summarized in Table 3.3.2.1.

1 **Table 3.3.2.1 Summary of possible application benefits from implementation of NEWS.**

2 **Change Variable/Issue                      NEWS Application Benefit**

<b><u>Weather &amp; Climate</u></b>	
Short Term Weather Prediction	<ul style="list-style-type: none"> <li>• Establish warning system for extreme event forecasting, floods and hurricanes.</li> <li>• Improve short term forecasts to Decision Support Systems</li> </ul>
Seasonal to Interannual Changes to water cycle	<ul style="list-style-type: none"> <li>• Improve 10-90 days water and air temperature forecasts.</li> <li>• Determine and predict interannual predictions for flora and fauna distributions energy planning.</li> </ul>
Anthropogenic Impacts	<ul style="list-style-type: none"> <li>• Assess Anthropogenic impacts to water and energy cycle.</li> </ul>
<b><u>Biogeochemistry</u></b>	
Carbon Cycle	<ul style="list-style-type: none"> <li>• Study and develop links with water and energy cycle.</li> </ul>
Other Nutrients (e.g. nitrogen)	<ul style="list-style-type: none"> <li>• Link water availability with nutrients for air and water quality.</li> </ul>
<b><u>Human Impacts</u></b>	
Water Quality	<ul style="list-style-type: none"> <li>• Improved water science/availability for assessments (e.g. concentrations, runoff etc.).</li> </ul>
Infectious disease	<ul style="list-style-type: none"> <li>• Further develop links (wet vs dry) using remote sensing.</li> </ul>
<b><u>Ecosystems</u></b>	
Coastal Areas	<ul style="list-style-type: none"> <li>• Assess changes to coastal areas from water cycle, sea level and wetlands loss.</li> </ul>
Sea Level Rise	<ul style="list-style-type: none"> <li>• Improve estimates of glaciers and ice sheets.</li> <li>• Study water budget, continental and ocean mass.</li> </ul>
Agriculture	<ul style="list-style-type: none"> <li>• Improve assessment and prediction of food production, and irrigation management.</li> <li>• Provide information for improved irrigation management..</li> </ul>
Flora and Fauna Distributions	<ul style="list-style-type: none"> <li>• Water and energy cycle changes significantly affects changes to flora and fauna distributions.</li> </ul>
<b><u>Water Availability</u></b>	
Precipitation	<ul style="list-style-type: none"> <li>• Provide local to global estimates for closing water budget.</li> <li>• Link to redistribution of energy through global heating.</li> </ul>
Snow and Ice	<ul style="list-style-type: none"> <li>• Improve snow extent over complex terrain</li> <li>• Develop techniques for snow water equivalent mapping.</li> </ul>
Ground Water	<ul style="list-style-type: none"> <li>• Direct estimates via GRACE and indirect estimates via modeling and remote sensing.</li> </ul>
Surface Runoff	<ul style="list-style-type: none"> <li>• Compensate for decline in ungauged basins.</li> <li>• Indirect (distributed modeling and direct (remote sensing)</li> </ul>
Soil Moisture	<ul style="list-style-type: none"> <li>• Improve from experimental to operational estimates.</li> </ul>

3

## 4 Elements of the NEWS Implementation Plan

NEWS is a coordinated research program to *document and enable improved, observationally-based, predictions of energy and water cycle consequences of Earth system variability and change*. The prediction system is built based on a global observing and assimilation system to determine the initial state of climate and a modeling system to make the forecast, both of which do not currently exist in complete or accurate form. Developing the prediction capability requires progressing through a repeating cycle of research elements: observations and retrievals, analysis, model development and testing, prediction, and demonstration of applications.

**Observations** are necessary to describe the state of the climate system, to determine the initial conditions for a model forecast of water changes, to provide a basis for testing the fidelity of numerical model simulations as measured by the accuracy of the forecasts, and to identify critical required improvements. **Analysis** of observational data is necessary to characterize climate variability, explore the limit of predictability of observed variations, and identify possible mechanisms. Further analysis or data assimilation is needed to evaluate model performance, initialize model forecast, and to identify causes of forecast errors. **Advanced climate models** are the necessary centerpiece of the prediction system because the climate is governed by a complex non-linear combination of coupled physical processes. Climate mechanisms can only be understood by experimenting with different (model) hypotheses. The key metrics to measure progress toward the ultimate objective of NEWS will be the accuracy of seasonal to inter-annual **predictions** of changes in precipitation and of water supply. Early versions of these predictions can also be employed to test **applications** to water resource management.

The implementation plan described below is organized in three successive phases calling out specific goals and milestones, thus defining successive stages in the development, validation and improvement of each component of the prediction system described above. Some activities in these phases would overlap. The emphasis during Phase-I is to adopt a process for promoting overall program integration in support of exploiting current capabilities and preparing for future developments of NEWS program elements. Phase-II focuses on addressing deficiencies and building a viable "prediction" system. Phase-III, focuses on the delivery of an end-to-end system to address the ESE vision, namely: comprehensive observations to accurately quantify the state and variability of the global water cycle, including data time series data sets with no significant gaps; routine analysis of variability of storage rates, transports and fluxes; routine prediction of key energy and water cycle parameters (including clouds and precipitation, radiation interactions and energy budgets, and surface hydrological parameters) and improved energy and water cycle forecasts for use in decision support systems. This section highlights the activities and milestones within the three chronologically successive Phases of NEWS with the caveat that various sub-tasks would by necessity overlap. The overall program goal is to ensure that advances in all the components of the science problem proceed on comparable paces and converge eventually to constitute a coherent water cycle prediction system. Coordination to maintain proper phasing of the research must not compromise the flexibility to exploit unexpected results or take unanticipated pathways. Specific measures of success (metrics) will be established by NASA management as a part of the overall planning process undertaken in consultation with the NSIT.



## 4.1 Phase 1: Exploiting Current Capabilities and Preparing for the Future (5 years)

The first phase focuses on the first coordinated attempt to describe the complete global energy and water cycle using existing and forthcoming satellite observations, and laying the foundation for essential NEWS developments in model representations of atmospheric energy and water exchange processes. This comprehensive energy and water data analysis program must exploit crucial datasets, some still requiring complete re-processing, and new satellite measurements. These data products will then be evaluated for accuracy and consistency, in part by using them in the first diagnosis of the weather-scale (space and time) variations of the global energy and water cycle over the past one-two decades. The primary objective is to ensure that results of this analysis effort serve as a recognized data basis to compare with corresponding climate statistics produced by existing climate models, quantify systematic deficiencies, and identify needed improvements. The data records to be produced through these efforts are mandatory for developing and validating models that meet NEWS scientific requirements.

At the same time, this implementation plan calls for the development of radically new model representations of energy and water exchange processes that resolve significant process scales and spatial variability in ground boundary conditions. Such process-resolving models may be first constructed as independent stand-alone modules that can be tested against *ad hoc* field measurements and systematic observations at selected experimental sites. At a later stage, the codes may be simplified through statistical sampling of process-scale variables or otherwise reduced to generate integrated fluxes representative of each grid-element in a climate model. Finally, the implementation plan calls for broad exploration of potential new observing techniques concerning all aspects of the energy and water cycle, and initiating relevant technical feasibility and scientific benefit studies.

Summary of Key Phase 1 Milestones	
<b>Observations and Retrieval</b>	<ul style="list-style-type: none"> <li>• Continue and enhance global measurements of clouds and aerosols, radiation vertical profiles</li> <li>• Assess methods for quantifying snowfall and mixed precipitation</li> <li>• Evaluate and invest in technology for observing land water storage</li> <li>• Evaluate global dataset adequacy and quality</li> <li>• Develop improved multi-sensor multi-variate geophysical retrieval methods</li> <li>• Quantify NEWS data requirements</li> </ul>
<b>Analysis</b>	<ul style="list-style-type: none"> <li>• Reduce uncertainties in describing the global water/energy cycle by 50%</li> <li>• Improve accuracy of precipitation and evaporation estimates</li> <li>• Develop new climate data products (e.g., latent and radiative heating profiles)</li> <li>• Quantify predictability of energy and water cycle variations (all spatial scales)</li> <li>• Develop diagnostic techniques for investigating how multiple feedback processes affect climate responses to forcings</li> </ul>
<b>Modeling and Prediction</b>	<ul style="list-style-type: none"> <li>• Improve current parameterizations of clouds and precipitation, land surface hydrology, atmospheric boundary layer and ocean mixed layer</li> <li>• Develop stand-alone ultra-high resolution cloud process and land hydrology models with atmospheric coupling for water/energy fluxes, soil moisture, runoff</li> <li>• Develop high resolution models for coupled clouds, radiation and hydrology</li> <li>• Test embedded process models in general circulation models</li> <li>• Develop and test advanced energy and water data assimilation methods</li> <li>• Quantify/evaluate causes/differences in precipitation predictions between global precipitation prediction models</li> <li>• Establish performance metrics for energy and water predictions</li> </ul>

<b>Applications</b>	<ul style="list-style-type: none"> <li>• Identify currently available data and analysis products useful for applications</li> <li>• Conduct selective demonstrations of usefulness of current data</li> <li>• Link weather &amp; climate predictions to demonstrate use in assessments of examples of representative consequences (e.g., extreme events)</li> <li>• Identify observation and prediction system requirements for water management applications</li> </ul>

#### 4.1.1 Observations and Retrieval

- Implement global measurements of *cloud and aerosol vertical distribution* (CloudSAT and CALIPSO missions) and the retrieval of cloud optical properties, particle/drop size distribution and physical properties. Develop methods for inferring atmospheric radiative heating profiles (radiation flux divergence) combining CloudSAT, CALIPSO, and MODIS/CERES/AMSR/ AIRS/PARASOL data.
- Assess the feasibility of combining visible, infrared and microwave remote sensing to quantify *snowfall and mixed precipitation* in preparation for the GPM program, identify freezing or melting ground, detect surface melting on sea ice and ice sheets, and in general characterize *cold land processes*. Examine the potential uses of CloudSAT radar data to quantify snowfall, and combined TRMM and CloudSAT data to estimate mixed precipitation. In cooperation with international partners, identify further measurement requirements for advanced GPM and Cold Land Process Pathfinder missions.
- *Explore potential advanced remote sensing methods* for global observation of land water storage in the form of soil moisture (possibly at several depths), inland water bodies and other important reservoirs, river discharge, and other relevant hydrologic quantities. Invest in required conceptual studies and *technology development*.
- Evaluate the *quality of global energy and water cycle datasets* and identify important deficiencies or gaps. The accuracy, completeness, and physical consistency of datasets based on operational observations may be evaluated by comparing to short-term experimental satellite measurements, extensive field campaign data (e.g., CEOP), and reference measurements from surface stations (e.g., ARM, BSRN). This quality assessment may also require technology investments to improve *in situ* sensors.
- Develop advanced multi-variate, non-linear, more rigorous *geophysical variable retrieval methods* based on physically consistent algorithms. Such development requires building new state-of-the-art radiation transfer models across the observed electromagnetic spectrum, including rigorous treatment of spectral dependence, polarization and coherent radiation. Also required are development of more effective algorithms (e.g., neural networks) that can handle non-linear relationships among a large number of variables and efficiently apply to large volume datasets such as the combined observations of the A-train, NPP and future NPOESS.

- Based on existing empirical and theoretical (model) knowledge, quantify NEWS data requirements, i.e. the nature, space/time sampling, and accuracy/precision needed for the different tasks envisioned in the program.

#### 4.1.2 Analysis

- **Using existing datasets**, assemble a complete description of global energy and water cycle to within 15%, including variability and changes. In cooperation with other agencies and international partners, review existing analysis procedures and implement consistent reprocessed analyses of essential long-term global datasets. Also needed are consistent time series of atmospheric state and circulation data, derived from operational analyses of basic meteorological observations or the reanalysis of archives. In cooperation with NWP centers, seek improvements in the accuracy of divergent wind field analyses.
- Improve the accuracy of **precipitation and evaporation** estimates over land and ice, and complete the datasets over continents, sea ice and ice sheets, through combined analysis of multiple satellite and surface measurements. The required additional inputs include surface skin temperature and soil wetness/melting indicators (combined infrared and microwave observations), near-surface humidity (atmospheric sounder suites), ocean surface wind velocity (active and passive microwave sensors), land-ice surface wind inferred from conventional weather observations and assimilation analysis. Merge the flux products with **water storage information** derived from SMOS, Aquarius and HYDROS measurements.
- Develop **new climate data products**, based on combined analyses of operational and experimental satellite measurements, and *in situ* reference measurements from surface networks such as the Baseline Surface Radiation Network, ARM-CART or similar facilities. In particular, investigate and exploit methods for inferring **latent and radiative heating profiles** (radiation and heat flux divergence) from vertical profile measurements by TRMM, CloudSAT, and CALIPSO, supplemented by A-train, POESS/NPOESS and METOP data. These results may be extended to longer periods using statistical models of cloud vertical structure related to different cloud systems observed by operational polar-orbiting and geostationary environmental satellites.
- Characterize weather-scale and longer-term variations in the global energy and water cycle using available global datasets, investigate possible trends, teleconnections and potential causal relationships and quantify the **predictability of energy and water cycle variations** on spatial scales, from weather systems to global, and time-averaging periods.
- Develop advanced non-linear, multi-variate **diagnosis/analysis techniques** to investigate how multiple feedback processes affect the climate response to various forcings.

#### 4.1.3 Modeling and Prediction

- Pursue **improvements in current parameterizations** of cloud and precipitation processes, land surface hydrology, and vertical transport in the atmospheric boundary layer and oceanic mixed layer. This work could be carried out using a range of models, from process-scale to regional and global, and from NWP models to fully coupled climate models. The outcome of this effort would be tested by comparing model outputs to observation-based global energy and water cycle datasets, notably surface radiation, heat, and water fluxes, and atmospheric transport data. The same non-linear, multi-variate analysis methods, developed for application to observations (see above), can be applied to model representations to assess how well dynamical relationships and extreme events are captured.

- Develop *stand-alone, ultra-high resolution cloud process models* that can resolve energy-containing scales of cloud systems dynamics, and explicitly represent cloud condensation processes (grid-scale microphysics), cloud water and ice, cloud particle size and properties. Likewise, develop stand-alone ultra-high resolution models of *land surface hydrology* and coupling with the atmosphere, for model computation of energy and water fluxes, soil moisture, and runoff. Assess the value of combining both types of models into a single integrated representation of *coupled cloud, radiation, and surface hydrology*. The outcome of this effort would be evaluated against detailed measurements from experimental sites (e.g. ARM-CART, TOGA-COARE, CEOP Reference stations) and *ad hoc* field experiments.
- Test the above process representations as *embedded modules in general circulation models* (GCM) capable of producing deterministic predictions of weather events and/or realistic simulations of weather-scale variability. Assess the performance of process-resolving models embedded in GCM computations (one-way coupling) against the same data as above.
- Develop and test *advanced energy and water data assimilation systems* that can ingest relevant atmospheric and hydrologic measurements and determine initial values for regional to global model predictions of variations or change in the global precipitation and hydrologic regimes.
- Conduct quantitative evaluations of *differences among global model predictions* of the energy and water cycle over seasonal to decadal time scales, and investigate the causes for such differences.
- Establish *performance metrics for energy and water cycle predictions* taking into account the limits of predictability of atmospheric and hydrologic variables over a range of space- and time-scales, from regional to global, and from weather time-scale to climate change.

#### 4.1.4 Applications

- *Identify currently available data and analysis products* that are useful for applications.
- Link weather and climate predictions to the *demonstration of some representative consequence*; notably consequences of extreme events. Evaluate the extent to which the information provided by current models is sufficient for such applications.
- Identify *observation and prediction system requirements* for water management applications.

#### 4.2 Phase 2: Integrating Essential Improvements into the Observation-Prediction System (5 - 7 years)

The second phase will focus on correcting the deficiencies identified in the first phase, exploiting and evaluating the newer measurements from recently deployed satellites (especially GPM), advancing multi-variate analysis procedures to exploit the full range of observations, and developing new measurement approaches for future flight missions. Simultaneously, the second phase includes implementing new process-resolving or otherwise improved representations of energy and water exchange processes in general circulation models (GCM), assembling a complete end-to-end data assimilation and prediction system for seasonal and shorter-range forecasts, and testing the predictions against observed transient variations or changes in climate statistics. An important objective of the second phase is to deliver useful seasonal predictions that can be applied to, and evaluated for their value to optimize water management decision-making.



	Summary of Key Phase 2 Milestones
<b>Observations and Retrieval</b>	<ul style="list-style-type: none"> <li>• Implement an experimental energy and water cycle observation system to acquire comprehensive observations of cloud structure &amp; optical properties, radiation fluxes, precipitation, atmospheric circulation, aerosols, for testing CRM's, GCM's and CCM's (A-Train)</li> <li>• Develop and implement advanced retrieval techniques for rain/snow, water vapor, wind etc., w/sampling density to directly determine transport, divergence terms, and soil moisture, water storage and freeze/thaw events</li> <li>• Identify and develop innovative remote sensing methods</li> <li>• Compare new remote sensing capabilities with in situ data from experimental sites and/or field campaigns</li> <li>• Form partnerships with operational agencies</li> </ul>
<b>Analysis</b>	<ul style="list-style-type: none"> <li>• Apply multi-variate analysis techniques in retrospective analysis of climate variability to investigate causes of natural variability and fast feedback processes, and discriminate between forced and unforced responses</li> <li>• Assess climate variability (short time scales) and forcing (longer time scales)</li> <li>• Assess the predictability of energy and water variations on range of space and time scales</li> </ul>
<b>Modeling and Prediction</b>	<ul style="list-style-type: none"> <li>• Develop simplified process resolving representations of precipitation and land hydrology for GCM simulations</li> <li>• Evaluate conventional parametric representations of clouds, precipitation, boundary layer, land hydrology in climate models compared with weather events and observed seasonal/interannual variations</li> <li>• Assess similarities and differences between model climate variability on short time scales and forced responses of models on longer time scales</li> <li>• Improve representation of slow feedback processes</li> <li>• Determine most informative model products for predicting water supply</li> <li>• Assemble experimental end-to-end energy and water cycle prediction system from observations to data assimilation, model initialization and prediction, to assessments of hydrological consequences and decision support systems</li> </ul>
<b>Applications</b>	<ul style="list-style-type: none"> <li>• Test ability to predict consequences of extreme hydrological events</li> <li>• Develop prediction skill metrics aiding decision making procedures</li> </ul>

## 2 4.2.1 Observations and Retrieval

- 3 • Implement an *experimental energy and water cycle observation system* combining  
4 operational environmental satellites, currently planned experimental satellite missions such  
5 as CloudSAT and CALIPSO, SMOS, HYDROS, Aquarius, GPM, and potential new  
6 exploratory missions (e.g. advanced remote sensing systems for solid precipitation, soil  
7 moisture, and ground water storage).
- 8 • *Develop and implement advanced* single- or multi-instrument *retrieval techniques* for  
9 estimating energy and water quantities. Develop and implement comprehensive multi-variate  
10 retrieval schemes that combine new satellite measurements (e.g. CloudSAT, CALIPSO,  
11 Aquarius, HYDROS, GPM, etc.) with conventional data from operational satellites and in

situ measurements to produce consistent combined retrievals of energy and water quantities.

- **Identify and develop innovative new remote sensing methods** for quantifying rainfall and snowfall, measuring atmospheric water vapor and wind with the sampling density required to directly determine water vapor transport and wind field divergence, estimating soil moisture (possibly at several depths), quantifying water storage in other reservoirs, identify freeze/thaw events. Continue to invest in relevant technological developments (especially active sounding techniques, such as lidars and radars, that can resolve the lower troposphere).
- **Test new remote sensing capabilities** against detailed *in situ* measurements from selected experimental sites or field experiments, as appropriate.
- Form **partnerships with operational agencies** for the continued collection, analysis, and archival of new or expanded global energy and water cycle datasets.

#### 4.2.2 Analysis

- **Apply multi-variate analysis techniques** to combine newly developed global data sets with older data products and determine energy and water exchanges associated with climate variability or climate change over the past few decades. Apply these analyses to the investigation of causes for natural variability and studies of fast feedback processes that allow discriminating between forced and unforced responses of the climate system. Quantify responses to different external forcings.
- Based on observational data sets, **assess the similarities and differences** between observed climate variability on shorter time scales and climate responses to forcing on longer time scales.
- Based on observational data sets, **assess the predictability of energy and water cycle** variations on a range of space-time scales, from weather-scale to decadal time scales and from regional variations to global change.

#### 4.2.3 Modeling and Prediction

- **Develop reduced process-resolving representations** of cloud, precipitation and land hydrology processes suitable for implementation in GCM simulations. Such reduced representation may be based on 2-dimensional representations of the full 3-D dynamics or other methods for sampling the variability and heterogeneity of real processes within GCM grid boxes. Test the accuracy of grid-box averages of energy and water fluxes computed by such reduced representations, and **evaluate impacts on GCM predictions** over a large, statistically compelling ensemble of observed weather events and seasonal to interannual variations, including extreme hydrological events (floods and droughts).
- Similarly **evaluate conventional parametric representations** of clouds, precipitation, boundary layer, and land hydrologic processes in climate models against individual weather events and observed seasonal or interannual variations. This task will require a capability for data assimilation and initialization of boundary or reservoir variables that govern weather, transient hydrologic events, and seasonal variations.
- **Assess the similarities and differences** between model climate variability on shorter time scales and the forced response of climate models on longer time scales.
- Improve the representation of the **slow feedback processes** involving, *inter alia* exchanges between land and coastal waters, river discharge in ocean basins, etc.

- In view of the observed and modeled predictability of energy and water cycle components, identify the most informative climate model prediction and/or deterministic forecast ***products for predicting water supply***. In cooperation with water management agencies and water resource managers, design and implement tests of this capability.
- Assemble an ***experimental, end-to-end energy and water cycle prediction system*** from measurement to data assimilation, model initialization and prediction, and assessments of hydrologic consequences. The system may involve several kinds of numerical models (from regional to global, and from NWP models to interactive climate-system models) for different purposes

#### 4.2.4 Applications

- Test ability to predict the ***consequences of extreme hydrological events***.
- Develop ***prediction skill metrics*** relevant to applications and management decisions.

### 4.3 Phase 3: Completing and Validating the Water Cycle Prediction System (2-5 yrs)

**The third phase** will focus on developing a capability for annual to decadal-scale climate predictions, in cooperation with the climate modeling community. The implementation plan calls for delivery of advanced atmospheric GCM formulations that can demonstrably predict changes in the energy and water cycle up to at least several seasons. An objective of the third phase will be testing against observations decadal predictions produced by fully interactive models of the complete climate system and/or simpler configurations involving the partial replacement of active components by observed boundary conditions. The third phase will also aim to deliver more penetrating tests of model performances using extended analyses of the widest possible range of observations, including some of the new global observing systems evaluated in the second phase.

Summary of Key Phase 3 Milestones	
<b>Observations and Retrieval</b>	<ul style="list-style-type: none"> <li>• Complete development of a full experimental energy and water cycle observing system</li> <li>• Develop a comprehensive data management and retrieval system</li> <li>• Reprocess the combined record of energy and water global observations using advanced retrieval methods</li> </ul>
<b>Analysis</b>	<ul style="list-style-type: none"> <li>• Characterize the slower feedback processes that effect the energy and water cycles</li> </ul>
<b>Modeling and Prediction</b>	<ul style="list-style-type: none"> <li>• Produce a fully interactive global climate system model that characterizes the complete energy and water cycle</li> <li>• Construct a comprehensive energy and water data assimilation and prediction system</li> <li>• Conduct a full end-to-end test of the prediction system against the past 30 to 50 year observational record</li> </ul>
<b>Applications</b>	<ul style="list-style-type: none"> <li>• Test the accuracy of energy and water cycle prediction products for applications to water resource management.</li> <li>• Demonstrate ability to predict consequences of climate change and hydrologic extremes</li> <li>• Demonstrate feasibility of a global hydrologic warning system</li> </ul>

### 2 4.3.1 Observations and Retrieval

- 3 • Complete the deployment of a ***full experimental energy and water cycle observing system***,  
4 that can support model predictions of the global energy and water cycle and hydrologic  
5 consequences.
- 6 • Develop a comprehensive ***data management and retrieval system***, including the advanced  
7 algorithms developed in the previous phases, that can be used by operational agencies in  
8 support of operational predictions and services; and conduct an end-to-end data system test
- 9 • Using advanced geophysical data retrieval algorithms, ***reprocess the combined record of***  
10 ***global observations*** from the A-train, NPP, NPOESS and other operational environmental  
11 satellites, CloudSAT and CALIPSO, SMOS, HYDROS and Aquarius, GPM, and other future  
12 satellite missions.

### 13 4.3.2 Analysis

- 14 • Characterize the most significant ***slower climate feedback processes*** that affect decadal  
15 predictions



### 4.3.3 Modeling and Prediction

- Integrate the component process models developed in the previous phases into *fully interactive global climate models or Earth-system models*. Evaluate the consistency of the predicted energy and water cycle on decadal or longer time scales, e.g. through verifying the balance of fresh energy and water fluxes and storage.
- Build a *comprehensive energy and water data assimilation and prediction system* that explicitly predicts the significant (energy containing) space- and time-scales of the energy and water cycle. Achieving this goal may involve developing a set of models with consistent physical process representations but different designs for different prediction objectives (e.g., regional, global short-term, global long-term models).
- Conduct a *full end-to-end test* of the prediction system against the past 30-50 year observation record to demonstrate the value of such simulations or predictions for practical applications, including the ability to predict extreme hydrologic events, out to decadal time scales.

### 4.3.4 Applications

- Test the accuracy of energy and water cycle *prediction products for application to water resource management*.
- Demonstrate ability to *predict the consequences* of climate change and hydrologic extremes for specific test cases.
- Demonstrate the feasibility of a *global hydrologic warning system*.

## 5 Linkages to NASA, National and International Programs

The broad national objectives of energy and water related climate research extend well beyond the purview of any single agency or program, and involve the support of activities that are essentially matched to each agency's respective roles and mission. Accordingly, NEWS will focus its priorities on scientific activities that are consistent with NASA's primary responsibilities in this area of research. In principle, NEWS does not plan to undertake significant research on all program elements, but looks to other NASA programs, other Federal agency programs, and the international community, as sources of essential data and knowledge. Examples include experimental and operational observations of air/sea fluxes, ocean circulation, atmospheric state, snow and ice; as well as support for the development of new general circulation models. In some cases, NEWS investments may be required to supplement these activities to ensure that they meet NASA needs, for example, *in situ* measurements of parameters that are essential to validating space based remote sensing, as well as quantities needed but not otherwise measured or derived.

### 5.1 Linkages with Other NASA Programs

The ESE research program aims to acquire deeper scientific understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life.

The energy and water cycle serves as an integrator within the Earth System connected to the other NASA themes and scientific disciplines. The energy and water cycle is itself cross-cutting, and must be studied through an integrated systems approach. It directly affects and controls the other components of the Earth system and, is conversely affected by their changes through processes involving energy and water storage, fluxes and feedbacks. These interactions occur on a continuum of temporal and spatial scales ranging from short-term weather to long-term climate and motions of the solid Earth, and from local and regional to global. Therefore, in the implementation of NEWS scientific research, it is important that the contribution and links to common NASA ESE goals are recognized and exploited.

#### 5.1.1 Linkages with ESE Focus Areas

ESE has established six scientific focus areas for these complex processes. These scientific focus areas are: Atmospheric Composition, Carbon Cycle and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather. ESE focus areas are interrelated and must eventually be integrated to arrive at a fully interactive and realistic Earth system representation. The integration of NEWS efforts with the efforts the other focus areas is essential for the implementation of this focus area. Therefore, the interdependencies of NEWS with each focus area are described here.

##### 5.1.1.1 Climate Variability and Change Focus Area

NEWS has several objectives that support the general area of Climate Variability and Change, while maintaining a specific focus with respect to the energy and water cycles. By concentrating on understanding the processes that control the hydrologic cycle, NEWS should enable better predictions of water vapor and cloud distributions, both for the current climate and, via improved models, for future climate changes. As these are the prime feedbacks determining climate sensitivity, the results will help us understand historical and decadal-scale climate responses to

both anthropogenic and natural forcing. The NEWS focus on determining required observations for understanding the hydrologic cycle and its changes will parallel some of the concerns of the climate change focus, and the target goal of being able to improve predictions of water availability changes will dovetail with the overall concerns of the Climate Variability and Change focus of improving societal understanding of potential consequences of climate perturbations.

The energy and water cycles are very clearly linked when considering the potential impacts of climate change on hydrology. Temperature gradients influence the intensity of the low-latitude Hadley Circulation, with its consequent areas of moist and arid conditions. In the extra-tropics, temperature gradients affect storm generation via baroclinic instability, influencing storm tracks and precipitation. The latitudinal temperature gradient is driven by the gradient in solar energy absorbed by the tropics (high) versus the poles (low). Future climate changes in net radiative forcing will likely occur associated with anthropogenic and natural forcings. The gradient will also be affected by the system feedbacks to these climates forcings, primarily the water vapor, cloud cover, vegetation and cryosphere responses. Additional feedbacks in atmospheric or ocean energy transports, for example changes in the North Atlantic deep ocean circulation thought to be sensitive to fresh water inputs, would result in further alterations. Any variation in temperature gradients will alter the particulars of the hydrologic cycle and water availability.

Therefore, the energy and water cycle diagnostics that are relevant to both focus areas include surface and top of atmosphere energy fluxes, cloud properties, water vapor, precipitation, soil moisture, vegetation water content, sea ice, sea surface salinity, and atmospheric and oceanic transports. The aerosol indirect effect and aerosol removal by precipitation represent important additional overlaps.

Required observations are consistent with current day assessments and decadal-scale trends. Among the relevant parameters are satellite surface radiation data sets (CERES, SRB), global precipitation measurements (GPM), and satellite surface turbulent flux data sets for latent and sensible heat fluxes (e.g. Sea Flux). Satellite retrieval of soil moisture to rooting depth is the major as yet unobtained quantity, strongly affecting both focus areas.

#### ***5.1.1.2 Carbon Cycle and Ecosystems Focus Area***

People have impacted the composition of the global atmosphere at alarming rates. Atmospheric greenhouse gas concentrations of carbon dioxide and methane have both increased approximately 30% since the beginning of the Industrial Revolution in the late 1700s. Increases of this magnitude have not occurred as far as the longest ice core record going back over 400,000 years. Increases in greenhouse gases may be contributing to changes in temperature and the water cycle.

Increases in the concentration of green house gases are the best understood factors that may contribute to climate change. Trace gases absorb the infrared radiation reducing the amount of heat lost to space. Carbon dioxide is the most abundant of the trace gases and recognized as likely the most important trace gas affecting the global water cycle and climate change. Approximately one-half of the fossil fuel combustion of CO<sub>2</sub> to the atmosphere is absorbed back by the oceanic and terrestrial ecosystems. However, the mechanisms and storage amounts are not completely understood.

The overall location and magnitude of global carbon sinks and sources are in doubt. Atmospheric CO<sub>2</sub> concentrations are affected by changes in the land and ocean sinks and the

terrestrial biomass and ocean dissolved organic carbon productivity. Hence without this understanding of carbon fluxes and sinks the prediction of the energy and water cycle (and climate change) is not attainable. Similarly, improvements in the estimates of heat and moisture fluxes over land and oceans will significantly reduce uncertainties in the carbon cycle. NASA is studying climate change by improving the interdisciplinary study of carbon and water with other factors in the land, ocean atmosphere system. Carbon and water also interlinked through similar pathways such as in plant photosynthesis where carbon dioxide is input through the same passage ways (i.e., stomates) that water is lost through transpiration

#### ***5.1.1.3 Weather Focus Area***

The mission of ESE is to develop the scientific understanding of the earth system using unique space-based observations, modeling, and data assimilation techniques. An expected outcome is improved predictive capabilities on a wide range of spatial and temporal scales relevant to decadal, interannual, seasonal, and monthly climate and short-term weather predictions. In 2015, the NASA Weather theme will deliver improvements in: 1) the zero to fourteen-day weather forecasting, 2) hurricane landfall predictions used for evacuation decisions, 3) prediction of hazardous winter-weather used to activate appropriate mitigation, 4), quantitative precipitation forecasts used to make economic decisions, and 5) regional nowcasting of severe weather to enable life-saving actions and to reduce false alarms. Given that the fast components of the energy and hydrologic cycles play an integral role in the development and subsequent consequence of weather events, it is imperative that NEWS and the Weather focus area identify common research areas and develop concise plans for crosscutting activities, such as observations or estimates of atmospheric wind profiles that affect atmospheric heat and moisture transports.

The Enterprise supports several joint NASA/NOAA programs that conduct research on the fast components of the energy and water cycle that must be integrated by NEWS. The Convection and Moisture Experiment (CAMEX) is focused on the study of tropical cyclone (hurricane) development, tracking, intensification, and landfall impacts using space-based, aircraft and surface remote sensing instrumentation. The project supports basic moist process studies, high-resolution modeling of the tropical storm and its environment, and advanced data assimilation activities. The Joint Center for Satellite Data Assimilation (JCSDA) is tasked with accelerating the use of satellite data within assimilation systems used to support zero to 10-day global operational forecasts produced by the National Centers for Environmental Prediction (NCEP). The JCSDA is a joint venture between the NASA Global Modeling and Assimilation Office (GMAO), NCEP Environmental Modeling Center, and the National Environmental Satellite, Data, and Information Service (NESDIS). The Short-term Prediction Research and Transition (SPoRT) Center is tasked with accelerating the use of EOS data, products, modeling and regional data assimilation techniques by NOAA operational forecasters. SPoRT conducts observational and modeling research associated with the flux of energy and moisture from the land surface to atmosphere, planetary boundary layer dynamics, cloud microphysics, moisture transport mechanisms, and severe storm kinematics.

#### ***5.1.1.4 Atmospheric Composition Focus Area***

Aerosol direct radiative forcing remains an area of low or very low scientific understanding (IPCC, 2001). While the direct radiative effect of aerosols, especially anthropogenic aerosols, is a forcing for climate variation and change and a part of the global energy cycle, the main uncertainties that affect this component of atmospheric radiation fluxes concern aerosol composition (in particular the amount of aerosol black carbon and other organic materials),



aerosol particle size distribution, and relationship of aerosol composition/amount to cloud condensation nuclei. The indirect effect of aerosols is associated with clouds and precipitation, a major component of the global energy and water cycle. As a result, this research field is most effectively handled in the Atmospheric Chemistry and Composition Focus Area.

#### ***5.1.1.5 Earth Surface and Interior Focus Area***

A key ESE goal is how the Earth's surface is being transformed and how can such information be used to predict future changes. The goal addresses solid Earth processes at the interface between the land, atmosphere, hydrosphere and cryosphere. The Solid Earth program includes studying the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change. A key component of the Solid Earth program is from the Gravity Recovery and Climate Experiment (GRACE). GRACE will greatly improve by several orders of magnitude more precise estimates of large bodies of ocean and terrestrial water mass. Another component linked to the water cycle is sea level change and its effects. For example, variations in Greenland ice height are important to monitoring changes to sea level and are indicators of climate change. The study of volcanoes is directly linked to the energy and water cycle, and the release of volcanic ash may also significantly affect climate through increases to atmospheric aerosols dramatically changing the global radiation and water budget.

#### **5.1.2 Linkages with ESE Research Disciplinary Programs (Code YS)**

The global Earth system environment can only be understood as an interactive system including the atmosphere, oceans, and land systems. The thrust of NASA ESE embraces multiple disciplines (e.g., atmosphere dynamics/physics/chemistry, hydrology, biology, oceanography, and geology), and requires integrated, cross cutting focus areas, as described above. NASA ESE goals are to obtain an understanding of the entire Earth system by describing how the component systems evolve, function, interact and may be predicted. Each of these focus areas cut across the traditional scientific disciplines reflected by the organizational structure of the ESE Research Division (Code YS), to apply multidisciplinary scientific knowledge to Earth system processes. Relevant ESE research disciplinary program linkages to the Water and Energy Cycle Focus Area are described here.

##### ***5.1.2.1 Atmospheric Dynamics***

The goal of the Atmospheric Dynamics program is to develop an understanding of the physical processes important in establishing the circulation of the atmosphere on all scales, ranging from the mesoscale to the global scale. This requires not only the study of the distribution and cycling of mass, energy, momentum and water vapor in the troposphere, but also the coupling of the dynamical and thermodynamical processes with the hydrological and radiative processes. The program addresses the following science plan questions; 1) How are global precipitation, evaporation, and the cycling of water changing? 2) How are variations in local weather, precipitation, and water resources related to global climate variation? and, 3) How can weather forecast duration and reliability be improved by new space-based observations, data assimilation and modeling? The program is linked to the Water and Energy Cycle Focus area via the following items; 1) Observations of tropical rainfall/energy release, 2) High-resolution global measurements of temperature, moisture, cloud properties, and 3) Global Precipitation Measurement.

##### ***5.1.2.2 Terrestrial Hydrology TBD (J. Entin)***

### 5.1.2.3 Atmospheric Radiation

The Radiation Sciences Program (RSP) seeks to develop a more quantitative scientific understanding of the Earth's energy budget. Some of the largest uncertainties in our understanding of the earth's radiation budget are associated with aerosols and clouds. In particular, our understanding of the magnitude of the role of atmospheric water as it affects aerosol size, cloud formation, and cloud properties are poorly known. The terrestrial water cycle, especially soil moisture, is a critically important and poorly quantified controlling process/parameter affecting atmospheric water; connecting the earth's radiation budget to terrestrial hydrology. For example, the flux of water from the earth's surface is important in the formation and properties of clouds. Atmospheric aerosols, acting as cloud condensation nuclei, can influence rain formation and rainfall rates which affect soil moisture content and, consequently, the flux of water from the earth's surface. Thus many of the important advances of interest to the RSP are dependent on complimentary advances in the Water and Energy Cycle focus area.

### 5.1.2.4 Land Cover Land Use Change

Changes in land use and land cover are an important component of global environmental change. NASA's Land-Cover and Land-Use Change (LCLUC) Program is one of the scientific programs within ESE. The LCLUC key science questions in this context are: 1) Where are land cover and land use changing, what is the extent and over what time scale? 2) What are the causes and what are the consequences of LCLUC? 3) What are the projected changes of LCLUC and their potential impacts? and 4) What are the impacts of climate variability and changes on LCLUC and what is the potential feedback?

The LCLUC Program is closely linked to the Water and Energy Cycle Focus Area due to both the impacts of changes in land use and land cover -- the drivers of the hydrologic cycle -- affecting ground surface and atmospheric hydrology and the impacts of hydrologic processes on LCLUC.

Among the major drivers affecting both surface and atmospheric hydrology are changes in agricultural or grazing practices, fires, forest exploitation and clearing, wetlands loss, urbanization, fresh water diversion (including construction of dams and artificial reservoirs), air pollution and other processes. The human forcing factors that result in changes of land cover and land use are manifested through land ownership or land management practices. Latent and sensible heat fluxes into the atmosphere are affected by land use through changes in land cover and other surface modifications, such as irrigation. Cloud microphysics is affected by aerosols from industry and forest fire smoke, leading to changes in rain regime. The science questions that are relevant here are: 1) Where are the current areas of rapid land-use and land-cover change at the national and global levels leading to land degradation and affecting water resources? and 2) What are the current patterns and attributes of land use and land cover at national to global scales that affect the atmospheric and surface hydrological processes?

In turn, variability in weather and climate drive land-cover changes on temporal scales from days (e.g. hurricanes) to years (e.g. persistent drought) to decades (e.g. global warming). Climatic and hydrologic variations and extremes can trigger persistent land-cover changes that will, in turn, impact land-atmosphere exchanges for long periods of time. Successive years of drought or above average rainfall, for example, can change land- use practices or the frequency of fires -- one of the major disturbances in forest cover. So the question is: how, and to what extent, do

such extreme events and hydrologic change and variability affect land-use and land-cover change?

#### **5.1.2.5 Modeling, Analysis and Prediction (MAP) TBD (D. Anderson)**

#### **5.1.2.6 Suborbital Sciences TBD (C. Yuhas)**

#### **5.1.2.7 Information Systems TBD (T. Lee)**

#### **5.1.2.8 Terrestrial Ecology**

The goal of NASA's terrestrial ecology and biogeochemistry research is to improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water. This research addresses terrestrial ecosystems as they are affected by human activity, as they change due to their own intrinsic biological dynamics, and as they respond to climatic variations and, in turn, affect climate. It requires strong scientific interactions with the Water and Energy Cycle focus area, recognizing that water is essential for all life and that vegetation exerts strong controls on fluxes of water into the atmosphere and the surface energy balance. Soil moisture, rainfall, and freeze-thaw dynamics are important controls on ecosystem productivity and carbon dynamics. Surface water flows are of major importance in the biogeochemical cycles. Changes in ecosystem properties and processes affect factors such as surface albedo and net radiation, the partitioning between latent and sensible heat fluxes, aerodynamic roughness, and boundary layer properties. Investigation of these interactions and feedback mechanisms are manifested by mutual support and analysis of certain measurements; joint involvement in cross-disciplinary projects, including field campaigns; and collaboration in Earth system modeling.

Many scientific issues in terrestrial ecology and biogeochemistry can only be addressed when high-quality supporting hydrological and climatic data sets are available. For example, systematic observations of surface temperature, humidity, rainfall, and incident solar radiation are needed to drive ecological models, and information on clouds and water vapor is needed to correct surface imagery. New satellite measurements being pursued by the Water and Energy Cycle focus area will play important supporting roles in terrestrial ecology research; these include measurements of surface soil moisture (to estimate soil water available to plants and drive ecosystem models), measurements of freeze-thaw transitions in vegetation and soils (for estimates of growing season length, which is the primary determinant of annual carbon uptake in high latitude terrestrial ecosystems), and measurements of surface water flows and river discharge (for estimates of the transport of biogeochemical constituents and of where anoxic conditions prevail so as to improve biogeochemical cycling models).

### **5.1.3 Linkages with ESE Applications Program (Code YO)**

The ESE science goals and activities are the driving forces that help support the NASA National Applications Program. The Applications Program mission is to: ***Expand and accelerate the realization of societal and economic benefits from Earth science, information and technology.*** The global energy and water cycle activities described in Section 2.3 and 3.2.4 will have a broad array of significant benefits to the Applications Program. Application results from the energy and water cycle research will be extensive, ranging over both multi-temporal (e.g., short-term floods to El-Nino/La Nino cycles) and multi-spatial (e.g., regional to global precipitation trends) scales.

The NASA National Applications Program has identified twelve theme areas to exploit the ESE

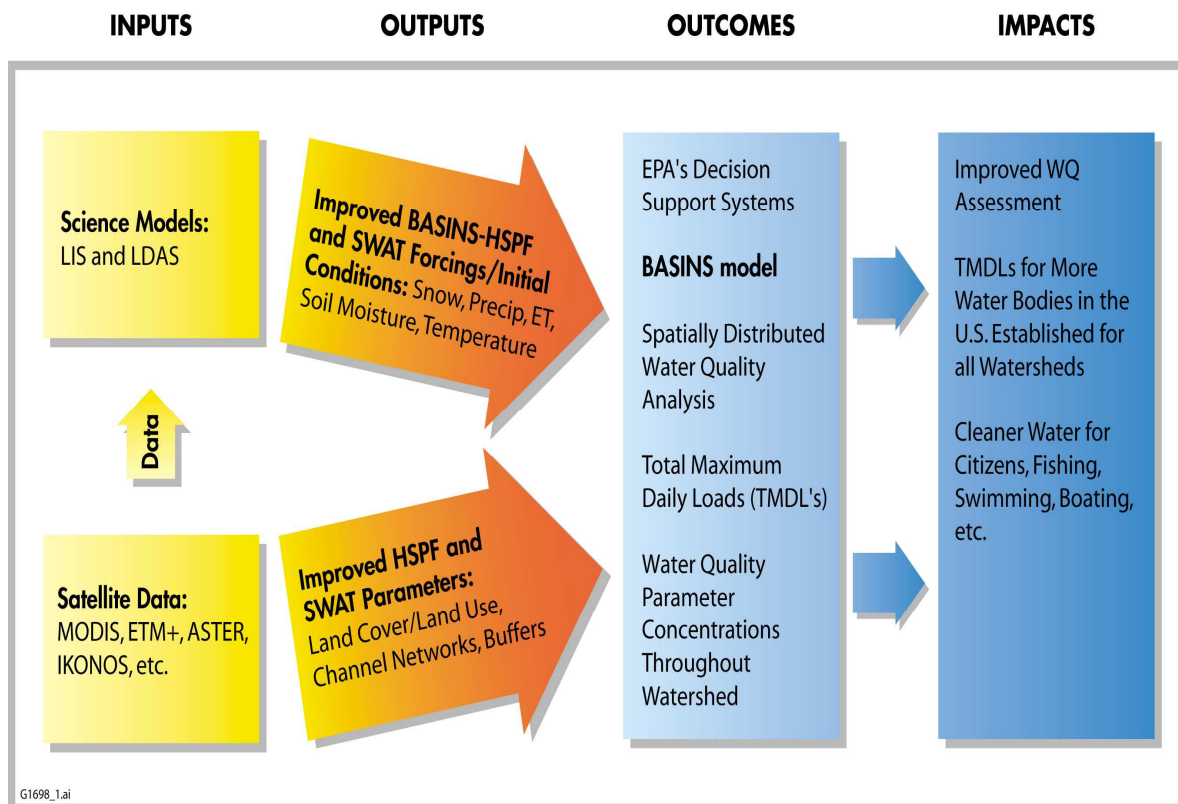
1 technologies (Figure 5.1). For each of the theme areas an engineering systems approach is used  
2 to incorporate remote sensing observations and modeling predictions to decision support tools.  
3 In this approach NASA data are evaluated verified/validated and benchmarked to study possible  
4 improvements. The primary emphasis of the Applications Program is to supply NASA data and  
5 information that may yield improvements to other groups, emphasizing US federal agencies  
6 having broad or national applications. The number of potential NASA partners for these  
7 application areas is large. NOAA, DOD, EPA, USDA, USBR, USGS, NMFS, NOAA-NESDIS,  
8 NIH, CDC, USFWS, BLM, FEMA, and more, plus state and local agencies (DEQ, etc.) all are  
9 potential users of a wide variety of information concerning the management of the Earth, and  
10 forecasts for future variability and change





The commercial application of NASA capabilities will only grow as new capabilities are developed to assess future changes, and thereby develop the ability to predict the effects of new commercial, regulatory and policy activities. The three phases of NEWS described in Section 4 will provide fundamental information to numerous NASA applications, such as to an early warning system for floods, and to aid the allocation of predicted available water into commercial, agriculture versus public consumption uses.

Currently, for example, the Water Management Program focuses on estimating water storages (snowpack, soil moisture, and aquifers) and modeling and prediction of water fluxes (evapotranspiration, precipitation and river runoff) to other federal agency decision support tools. Figure 5.2 shows an example application of using NASA data into Decision Support Systems (DSS) such as to the “BASINS” model, emphasizing nonpoint source water quality used by U.S. Environmental Protection Agency.



**Figure 5.2:** *Schematic of the approach for developing and implementing NASA remotely sensed and modeling products into EPA DSS's and modeling tools.*

Similar work studying the use of NASA data is ongoing with the US Bureau of Reclamation using “RiverWare” to regulate reservoirs and “AWARDS - ET Toolbox” for estimating water loss, and the US Department of Agriculture using “SWAT” for soil-water availability DSS. In addition, due to the crosscutting nature of energy and water cycle research forthcoming from NEWS there is a broad range of applications that can benefit from improved understanding and prediction of the global energy and water cycle. Water/energy applications and results from NEWS is also closely linked and integrated with many of the other NASA focus areas including Disaster Management (e.g., floods), Agriculture Efficiency (e.g., water availability), Air Pollution (e.g., atmospheric nitrogen deposition to surface water), Invasive Species (e.g., water consumption) and Coastal Zones (e.g., water availability and quality).

#### 5.1.4 Linkages with ESE Technology Programs (Code YF)

NASA’s ESE conducts a technology program that develops advanced technical capabilities for future ESE science and applications systems. Advanced technologies provide the foundation for a new generation of sensors, instruments, information systems, and high-end modeling frameworks. When infused into mission systems, new technologies yield improvements in our ability to observe, process, and disseminate data and information products to ESE customers.

The Earth Science Technology Office (ESTO) is responsible for development of a comprehensive technology-investment portfolio that meets NEWS needs. A crucial part of this role is the integration of ESE technology management and strategic planning activities into a single program that maintains an effective balance of the overall technology investment. This role includes fostering of cooperative relationships with internal NASA programs and partnering with other federal agencies, academia, and private industry.

Using NEWS research program needs as the focal point, ESTO identifies promising scientific and engineering concepts and supports their development. ESTO identifies capability needs from NEWS science and applications objectives and maintains traceable links between these needs and technologies in the investment portfolio. These activities are implemented through a process whereby ESTO:

- **Plans** instrument and information systems technology based on annual-needs reviews held in collaboration with the NEWS community. These activities identify specific technology needs that drive the focus of technology solicitations.
- **Develops** technologies through competitive solicitations that are evaluated through a peer review process and monitored via on-line Award Administration e-Books.
- **Infuses** mature technologies into future science measurements. ESTO collaborates with NEWS investigators to identify short-, mid-, and long-term infusion opportunities for new science measurements.
- **Leverages** technology development investments through internal NASA program synergy and partnerships with other federal agencies, academia, and industry.

Development activities within ESTO are executed by the following program elements:

- **Advanced Technology Initiatives (ATI)**—provides for concept studies and development of component and subsystem technologies for instruments and platforms.
- **Instrument Incubator Program (IIP)**—provides new instrument and measurement techniques including lab development and airborne validation.
- **Advanced Information Systems Technologies (AIST)**—provides innovative on-orbit and ground capabilities for the communication, processing, and management of remotely sensed data and the efficient generation of information.
- **Computational Technologies (CT)**—provides techniques and systems that enable high performance throughput, archiving, data manipulation, and visualization of very large, highly distributed remotely sensed data sets consistent with modeling needs
- **Verification**—provides flight validation for breakthrough technologies at the system and subsystem level.

## **5.2 Interagency Partnerships**

### **5.2.1 The US Climate Change Science Program**

NASA's Energy and Water cycle Study (NEWS) would be a major contributor to the interagency coordinated efforts planned under the National Climate Change Science Program (CCSP) which incorporates the US Global Change Research Program (USGCRP) and the Presidential Climate Change Research Initiative (CCRI).

The strength of the USGCRP has been to facilitate coordination across Federal departments and agencies with active global change research activities, drawing on the resources and expertise of both research and mission-oriented agencies. Participants in the USGCRP include the Departments of Agriculture (USDA), Commerce (National Oceanic and Atmospheric Administration) (DOC/NOAA), Defense (DoD), Energy (DOE), Health and Human Services (National Institutes of Health) (HHS/NIH), Interior (U.S. Geological Survey) (DOI/USGS), Bureau of Reclamation (BOR), State (DOS), and Transportation (DOT); the U.S. Environmental

Protection Agency (EPA); the National Aeronautics and Space Administration (NASA); the National Science Foundation (NSF); and the Smithsonian Institution (SI). The Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) provide oversight on behalf of the Executive Office of the President.

In spite of USGCRP's significant successes over the past decade, the base of information for decision making remains inadequate. In a report commissioned by the Bush Administration, *Climate Change Science: An Analysis of Some Key Questions*, the U.S. National Academy of Sciences (NAS 2001) evaluated uncertainties and research opportunities and made a number of recommendations. At the most fundamental level, the report indicated the need to better understand the causes of warming. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability."

The report also identified areas where additional research is crucial. These included the magnitude and nature of future human-caused "forcings" such as emissions of greenhouse gases; the carbon cycle; "feedbacks" caused by water vapor, ice, and other factors that determine the response of the climate system; regional and local climate change consequent to an overall global level of change; the nature and causes of natural variability; and the direct and indirect effects of the changing distribution of aerosols (including black carbon). In addition, the report also called for accelerated research on the interactions of environmental change and human societies, including interdisciplinary research on coupled human-environment systems; integration of knowledge, including its uncertainty, into decision support systems; and regional or sectoral research into the response of human and natural systems to multiple stresses. Finally, the report noted that an effective strategy for advancing the goal of understanding climate change will require enhanced global observing systems; large-scale modeling; and more effective management of resources to ensure innovation, effectiveness, and efficiency.

CCRI introduces a new dimension to the research carried out under the USGCRP. Over the coming decade, the objective of Federally supported research programs will be to help government, businesses, and communities make informed management decisions about global environmental changes, such as climate change, given persistent uncertainties. Realizing this vision will require the continuation of research on how the Earth's climate and environment are responding to simultaneous changes in both natural forces and human activities. The USGCRP and CCRI will also develop new ways to transform scientific information into products for routine use by government and the private sector for reducing risks and taking advantage of opportunities resulting from global change.

Working as an integrated program, the USGCRP and CCRI will accelerate the transition of scientific knowledge to applications for use in resource management, disaster preparedness, planning for growth and infrastructure, and environmental and health assessment, among other areas. Partnerships with operational entities and associations in the private sector, and state and local governments, will be essential for focusing research and meeting the growing demands for relevant information to, for example:

- Reduce uncertainties for farmers by improving lead times and specificity of seasonal climate forecasts, enabling farmers to plant crops best suited to weather and environmental conditions.
- Facilitate continued safe and economic management of dams and other reservoirs by providing integrated forecasts of water demand and availability



- Support strategies for managing carbon by preparing periodic assessments of changes in carbon sources and sinks resulting from variations in climate, soil conditions, nutrients, and other factors
- Increase energy security and reduce the potential for climate-related shortages by developing the capacity to routinely forecast the implications of seasonal variations in climate for regions of the United States

### **5.2.2 The CCSP Global Water Cycle Research Program (GWC)**

The global energy and water cycle is represented under the CCSP (USGCRP + CCRI) by the CCSP Global Water Cycle Program (GWC). The energy and water cycle is directly involved in all “themes” of the CCSP including all the major observational, process research, and climate prediction and applications objectives of the CCSP. Indeed, most the major sources of uncertainty in climate change predictions/projections involve GWC processes such as water vapor, precipitation, and cloud-radiation feedback among others. For the assessment of the impacts of climate variability and climate change, changes in water cycle parameters are even more important than temperature changes in the context of agriculture, water resources, ecosystems, energy, and social and economic sectors.

NASA’s NEWS is fully integrated with the science and applications objectives of the CCSP-GWC which addresses the following overarching/strategic science and societal questions/issues:

- How does water cycle variability and change caused by internal processes, climate feedbacks and human activities influence the distribution of water within the Earth System, and to what extent is this variability and change predictable?
- What are the potential consequences of global water cycle variability and change for society and the environment, and how can knowledge of this variability and change improve water-cycle dependent decisions?

US Agencies with major programs and activities relevant to NASA’s NEWS’s research objectives include, the Department(s) of Commerce (DoC), Energy (DoE), Interior (DoI), Agriculture,(DoA) the National Science Foundation (NSF), and the Environmental Protection Agency (EPA). These other programs provide substantial research, observational (especially, in-situ) and operational applications assets which compliment NASA’s areas of specialization.

Examples of interagency collaboration between NASA's Energy and Water Cycle and the programs of other agencies include NASA/NOAA jointly funded GAPP (GEWEX Americas Prediction Project) projects on improving water demand analysis and prediction for water managers using a combination of satellite, radar and surface observations, and numerical weather forecasts, with land surface modeling to integrate Land data Assimilation Systems (LDAS) information into water operations decision support systems. The above and other projects also include active collaborations with agencies such as BOR, USDA/ARS and USGS. Coordinated activities in field campaigns include those with DOE/ARM for cloud, radiation and process modeling. NASA research collaborations include those with various efforts under NSF in the research development of improved observations and models for weather forecasting, seasonal-to-interannual (and longer) climate variability predictions and climate change projections.

### 5.3 International Partnerships

NASA's energy and water research connection to the international science community is through the World Climate Research Programme (WCRP), especially the Global Energy and Water Experiment (GEWEX), but including aspects of CLIVAR and CLiC. GEWEX has overall international WCRP responsibility for providing an interface with all the national space agencies with respect to energy and water cycle related global climate research requirements, instruments, data, science support. The GEWEX emphasis on improved coupled land-surface and atmosphere representations in prediction models at all scales has illustrated the direct links to the water cycle and has provided increased importance of both existing and future satellite sensing of the land and near surface parameters. GEWEX has set the stage for broader issues to be addressed within IGOS, and the Earth System Science Partnership (ESP) activities.

For example, the Global Water Cycle theme has been established by the IGOS Partnership, in which NASA plays a major role, to develop and promote strategies to maintain continuity for observing systems for the global water cycle and to progress towards an integrated water cycle observational system that integrates data from different sources (e.g., satellite systems, in-situ networks, field experiments, new data platforms) together with emerging data assimilation and modeling capabilities. It provides a framework for guiding decisions regarding priorities and strategies for the maintenance and enhancement of observations to support: monitoring of climate variability and change, effective water management and sustainable development of the world's water resources, societal applications for resource development and environmental management, specification of initial conditions for numerical weather and water forecasts and monthly to seasonal climate predictions and, research directed at priority water cycle questions. The theme also promotes strategies that will facilitate the acquisition, processing and distribution of data products needed for effective management of the world's water resources. To achieve these goals the initial activities will rely on the space based and in-situ networks that are either currently in place or planned. Furthermore, it must engage the global community through multiple linkages to global programs and coordinated activities.

In the context of global change, the Global Water System is defined as the suite of interacting physical, chemical, biological and human components that constitute and influence the fluxes of water on Earth, including the various uses of water for human well-being. The Global Water System Project (GWSP), jointly sponsored by IGBP, IHDP, WCRP and DIVERSITAS addresses the threatened sustainability of the global water system to a growing demand for water in many regions, exceeding water availability, and the degradation of water quality and subsequent ecosystem health effects associated with extreme events such as floods and droughts. GWSP will stress regional studies over a wide range of space and time scales associated with the processes that control water availability and quality.

These GEWEX related projects have already defined some paths and linkages for above initiatives and have shown areas where direct connections to the water resource societal applications can be made more cost effective. GEWEX helps NASA leverage international resources, providing added value to new satellite data, assisting in bringing in added satellite calibration/validation data sources, and delivering independent observationally-based data sets for evaluating model 4-dimensional data assimilation (4DDA) and prediction capabilities on a regional and global basis. For example, the ongoing WCRP Coordinated Enhanced Observing Period (CEOP) management is designed to take advantage of the new NASA Earth observing satellites to document and simulate energy and water fluxes and reservoirs over land, regionally,

on diurnal to annual scales, and transfer this knowledge to the global scale for water resources applications.

Specific GEWEX radiation, hydrometeorology, modeling, and energy and water cycle related prediction projects which contribute to meeting NASA Earth science objectives, and benefit from major NASA investments in both resources and scientific staff involvement include:

- International Satellite Cloud Climatology Project (ISCCP)
- Surface Radiation Budget (SRB) Project
- Global Precipitation Climatology Project (GPCP)
- Global Aerosol Climatology Project (GACP)
- Surface Turbulent Air/Sea Flux Study (SeaFlux)
- Baseline Surface Radiation Network (BSRN)
- GEWEX Cloud System Study (GCSS)
- GEWEX Global Land/Atmosphere Study (GLASS)
- Global Soil Wetness Project (GSWP)
- GEWEX Atmospheric Boundary layer Study (GABLS)
- International Satellite Land-Surface Climatology Project (ISLSCP)
- GEWEX Americas Prediction Project (GAPP)
- GEWEX Coordinated Enhanced Observing Period (CEOP)

NASA has also played a leading role in the international management and coordination of GEWEX as a U.S. national contribution to the WCRP for the past decade. In this context, NASA provides primary financial support to the International GEWEX Project Office (IGPO) operated by the University of Maryland, Baltimore County through a grant administered in conjunction with a Cooperative Agreement with the Goddard Space Flight Center. The IGPO provides the primary organizational support for planning and implementing the full range of GEWEX observations, modeling, and data management activities and serves as the principal WCRP interface with NASA and the other space agencies. This NASA-University affiliation provides a unique opportunity to explore a wider range of applications on human dimensions and environmental policy issues through engagement of the policy science and engineering faculty. The IGPO will also serve on the Executive Board of the IGOS Water Cycle theme.

New opportunities for promoting effective international coordination of space-based Earth observing systems will be made available through arrangements resulting from the first Earth Observations Summit, held in Washington DC in July 2003. NASA will play a central role in the *ad hoc* Group on Earth Observations (GEO), established to improve coordination of strategies and systems for earth observations and to identify measures to minimize data gaps, with a view to moving toward a comprehensive, coordinated, and sustained Earth observation system or systems.

## 6 Management

### 6.1 NEWS Program Management

The scientific framework for the Water and Energy Cycle Focus Area is outlined in the NASA Earth Science Enterprise Strategy document, issued in October 2003. It is one of six focus areas that define the scientific content of the NASA Earth Science program, and includes both research and technology components. Overall management responsibility resides in the Research Division (Code YS) of the Office of Earth science (Code Y) at NASA Headquarters. This responsibility includes: (1) overall budget authority, (2) control of periodic research and technology solicitations through the NRAs and AO process, and (3) primary interagency and international coordination. Only aspects of item (3) can be delegated to the NASA Field Centers.

#### 6.1.1 NEWS Science Integration Team

Pursuant to the overall NASA goal of understanding the Earth system and applying Earth system science to improving the prediction of climate, weather and related natural hazards, the Associate Administrator for Earth Science established a NASA Energy and Water cycle Study (NEWS) Science Integration Team (NSIT) to develop a comprehensive implementation plan for the Water and Energy Cycle Focus Area. The NSIT will cover all elements of energy and water research and technology, and provide a liaison with the other ESE research focus areas.

Exchanges of energy and water within the Earth system involve a multiplicity of interactive processes. Understanding and predicting these processes require a complex multi-disciplinary research program, innovative observing tools, and advanced model developments. Organizing these complex activities calls for new management and oversight approaches to ensure that both financial and human resources are efficiently applied to serve NASA Earth Science priorities.

To assist ESE management in the planning of this research effort, the NSIT will responsible for:

- Drafting and periodically updating the NEWS Implementation Plan, consistent with the ESE Research Strategy, the objectives of the Global Water and Energy Cycle research focus area, and current and emerging research opportunities and priorities
- Assisting ESE in the preparation of new research solicitations relevant to Global Energy and Water Cycle research\*
- Reviewing the performance of NEWS Discovery-driven and Product-driven individual research projects and assessing the overall progress toward achieving the established goals of NEWS
- Assisting ESE in developing new budget initiatives for NEWS-relevant research and/or observing systems elements \*
- Assisting Code YS Disciplines in the Peer Review process for NEWS-relevant proposals

The NSIT membership will consist of:

- The ESE Program Manager responsible for the NEWS research focus area
- Representatives (for coordination) designated by each of the other ESE research focus areas responsible for energy and water related research elements (Atmospheric Composition,



- 1 Carbon Cycle and Ecosystems, Climate Variability and change, Earth Surface and Interior,  
2 and Weather)
- 3 • Principal Representatives from NASA Centers which implement major NEWS-related  
4 programs (GSFC, GISS, LaRC, MSFC, JPL),
- 5 • Representatives from a sub-set of the Product-driven and Discovery-driven NEWS research  
6 Projects (to be nominated by the ESE NEWS Program Manager),
- 7 • Additional representatives from the scientific community, selected on the basis of their  
8 unique experience, but ineligible to compete for NEWS resources.
- 9 The NSIT Chair will be nominated by NASA Headquarters and serve for a term of 3 years. The  
10 NSIT will meet at times and locations scheduled by the Chair.
- 11
- 12 \* **Restricted to NASA civil servants**

## Appendices

### A.1 NEWS Science Integration Team

#### A1.1 NEWS Team Members

Dr. Jared K. Entin NASA Headquarters Code YS 300 E Street, SW Washington DC 20546-0001 <a href="mailto:jentin@hq.nasa.gov">jentin@hq.nasa.gov</a>	Dr. Paul R. Houser NASA/Goddard Space Flight Center Code 974 Greenbelt, MD 20771 <a href="mailto:Paul.R.Houser@nasa.gov">Paul.R.Houser@nasa.gov</a>
Dr. Robert A. Schiffer Goddard Earth Sciences & Technology Center (GEST) University of Maryland, Baltimore County Technology Center, South Campus, Room 3.002 1450 South Rolling Road Baltimore, MD 21227 <a href="mailto:schiffer@umbc.edu">schiffer@umbc.edu</a>	Dr. C. Adam Schlosser MIT Dept of Earth, Atmospheric and Planetary Sciences 77 Massachusetts Ave Cambridge, MA 02139 <a href="mailto:casch@mit.edu">casch@mit.edu</a>
Dr. William M. Lapenta NASA/Marshall Space Flight Center SD60 320 Sparkman Drive Huntsville, AL 35805 <a href="mailto:bill.lapenta@msfc.nasa.gov">bill.lapenta@msfc.nasa.gov</a>	Dr. William B. Rossow NASA/ Goddard Institute for Space Studies 2880 Broadway New York, NY 10025 <a href="mailto:William.B.Rossow@nasa.gov">William.B.Rossow@nasa.gov</a>
Dr. Bing Lin NASA/ Langley Research Center Mail Stop 420 Hampton, VA 23681-2199 <a href="mailto:Bing.Lin-1@nasa.gov">Bing.Lin-1@nasa.gov</a>	Dr. Eni G. Njoku Jet Propulsion Laboratory, M/S 300-323 4800 Oak Grove Drive Pasadena, Ca 91109 <a href="mailto:eni.g.njoku@jpl.nasa.gov">eni.g.njoku@jpl.nasa.gov</a>
Dr. Parminder S. Ghuman NASA/Goddard Space Flight Center Code 407.0 Greenbelt, MD 20771 <a href="mailto:Parminder.S.Ghuman@nasa.gov">Parminder.S.Ghuman@nasa.gov</a>	

## A1.2 Contributors

<p>Dr. Pierre Morel Goddard Earth Sciences &amp; Technology Center (GEST) University of Maryland, Baltimore County Technology Center, South Campus, Room 3.002 1450 South Rolling Road Baltimore, MD 21227 <a href="mailto:morel@hsb.gsfc.nasa.gov">morel@hsb.gsfc.nasa.gov</a></p>	<p>Dr. Bruce A. Wielicki NASA Langley Research Center Mail Stop 420 Hampton, VA 23681 <a href="mailto:b.a.wielicki@nasa.gov">b.a.wielicki@nasa.gov</a></p>
<p>Dr. Michael Jasinski NASA/Goddard Space Flight Center Code 974 Greenbelt, MD 20771 <a href="mailto:Michael.F.Jasinski@nasa.gov">Michael.F.Jasinski@nasa.gov</a></p>	<p>Dr. David Rind NASA/ Goddard Institute for Space Studies 2880 Broadway New York, NY 10025 <a href="mailto:David.H.Rind@nasa.gov">David.H.Rind@nasa.gov</a></p>
<p>Mr. David Toll NASA/Goddard Space Flight Center Code 974 Greenbelt, MD 20771 <a href="mailto:David.L.Toll@nasa.gov">David.L.Toll@nasa.gov</a></p>	<p>Dr. Waleed Abdalati NASA/Goddard Space Flight Center Code 971 Greenbelt, MD 20771 <a href="mailto:Waleed.Abdalati@nasa.gov">Waleed.Abdalati@nasa.gov</a></p>
<p>Dr. Eric A. Smith NASA/Goddard Space Flight Center Code 912.1 Greenbelt, MD 20771 <a href="mailto:Eric.A.Smith@nasa.gov">Eric.A.Smith@nasa.gov</a></p>	<p>Dr. Ramesh Kakar NASA Headquarters Washington, DC 20546-0001 <a href="mailto:ramesh.k.kakar@nasa.gov">ramesh.k.kakar@nasa.gov</a></p>
<p>Dr. Peter Hildebrand NASA/Goddard Space Flight Center Code 970 Greenbelt, MD 20771 <a href="mailto:Peter.Hildebrand@nasa.gov">Peter.Hildebrand@nasa.gov</a></p>	<p>Dr. Loren Lemmerman Jet Propulsion Laboratory, M/S 300-323 4800 Oak Grove Drive Pasadena, Ca 91109 <a href="mailto:Loren.A.Lemmerman-103246@jpl.nasa.gov">Loren.A.Lemmerman-103246@jpl.nasa.gov</a></p>
<p>Dr.Sushel Unninayar Goddard Earth Sciences &amp; Technology Center (GEST) University of Maryland, Baltimore County Technology Center, South Campus, Room 3.002 1450 South Rolling Road Baltimore, MD 21227 <a href="mailto:Sushel.Unninayar@gsfc.nasa.gov">Sushel.Unninayar@gsfc.nasa.gov</a></p>	<p>Ms. Deborah Belvedere NASA/GSFC, UMBC/GEST Code 974 Greenbelt, MD 20771 <a href="mailto:debbieb@hsb.gsfc.nasa.gov">debbieb@hsb.gsfc.nasa.gov</a></p>

## A.2 References

*Earth Science Enterprise Strategic Plan*, NASA Headquarters, November 2000

*Climate Change 2001 Report*, (IPCC, 2001)

*A Plan for a New Science Initiative on the Global Water Cycle*, USGCRP Water Cycle Study Group, May 2001

*Climate Change Science: An Analysis of Some Key Questions*, the U.S. National Academy of Sciences (NAS 2001)

*ESE, 2002: Report from the Earth Science Enterprise Computational Technology Requirements Workshop*

*Strategic Plan for the U.S. Climate Change Science Program*, Report by the Climate Change Science Program and the Subcommittee on Global Change Research, July 2003



### A.3 Acronyms

4DDA	four dimensional data assimilation	DMSP	Defense Meteorological Satellite Program
ACT	Advanced Component Technology	DoC	Department of Commerce
AIRS	Atmospheric Infrared Sounder	DoD	Department of Defense
AIST	Advanced Information Systems Technologies	DoE	Department of Energy
AMASS	data technology company	DoI	Department of the Interior
AMIP	Atmospheric Model Intercomparison Project	DoS	Department of State
ANSI/AIIM MS66	File storage management systems	DoT	Department of Transportation
Aqua	NASA Earth Observing Satellite mission for water	DSS	Decision Support Systems
ARM-CART	Atmospheric Radiation Measurement/Cloud and Radiation Testbed	Terra	Earth Observing Satellite to measure the land surface
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer	EPA	Environmental Protection Agency
Aura	NASA Earth Observing satellite mission for ozone, air quality and climate	ESE	Earth Science Enterprise
AWARDS	Agriculture Water Resources Decision Support	ESSP	Earth System Science Pathfinder
BLM	Bureau of Land Management	ESTO	Earth Science Technology Office
BSRN	Baseline Surface Radiation Network	ENVISAT	European satellite to measure land, ocean, atmosphere and ice caps
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	European METOP	Europe's first polar-orbiting satellite
CAMEX	Convection and Moisture Experiment	FEMA	Federal Emergency Management Agency
CCRI	Climate Change Research Initiative	FSMS	File Storage Management Systems
CCSP	Climate Change Science Program	GABLS	GEWEX Atmospheric Boundary Layer Study
CDC	Center of Disease Control	GACP	Global Aerosol Climatology Project
CEOP	Coordinated Enhanced Observing Period	GAPP	GEWEX Americas Prediction Project
CEOS	Committee on Earth Observation Satellites	GCIP	GEWEX Continental-Scale International Project
CERES	Clouds and the Earth's Radiant Energy System	GCM	General Circulation Model
CLIC	Climate and Cryosphere Project	GCOS	Global Climate Observing System
CLIVAR	Climate Variability and Predictability	GCSS	GEWEX Cloud System Study
CloudSAT	Cloud Satellite	GEOSS	Global Earth Observing System of Systems
CMIP	Coupled Model Intercomparison Project	GEWEX	Global Energy and Water Experiment
CRM	Cloud-Resolving Models	GIS	Geographical Information System
CT	Computational Technologies	GISS	Goddard Institute for Space Studies
DBMS	Database Management System	GLASS	GEWEX Global Land/Atmosphere Study
DEQ	Department of Environmental Quality	GMAO	Goddard Model Assimilation Office
DIVERSITAS	international global environmental change research programme	GPCP	Global Precipitation Climatology Project
		GPM	Global Precipitation Measurement
		GRACE	Gravity Recovery and Climate Experiment
		GSFC	Goddard Space Flight Center
		GSWP	Global Soil Wetness Project

GWC	Global Water Cycle	NOAA	National Oceanic and Atmospheric Administration
GWSP	Global Water System Project	NPOESS	National Polar-orbiting Operational Environmental Satellite System
HHS	Health and Human Services	NPP	NPOESS Preparatory Project
HSPF	Hydrological Simulation Program-Fortran	NSF	National Science Foundation
HYDROS	Hydrosphere State mission	NSIT	NEWS Science Integration Team
ICESat	Ice, Clouds, and Land Elevation Satellite	NWP	Numerical Weather Prediction
IGBP	International Geosphere-Biosphere Program	OMB	Office of Management and Budget
IGOS	Integrated Global Observing Strategy	OSTP	Office of Science and Technology Policy
IGPO	International GEWEX Project Office	QuikSCAT	Satellite mission for ocean surface wind measurements
IHDP	International Human Dimensions Program.	RiverWare	decision support tool
IIP	Instrument Incubator Program	RSP	Radiation Sciences Program
IKONOS	high resolution satellite imagery	SAR	Synthetic Aperture Radiometer
ISCCP	International Satellite Cloud Climatology Project	SeaFlux	Surface Turbulent Air/Sea Flux Study
ISLSCP	International Satellite Land Surface Climatology Project	SI	Smithsonian Institution
JCSDA	Joint Center for Satellite Data Assimilation	SMOS	Surface Meteorological Observation System
JPL	Jet Propulsion Laboratory	SORCE	Solar Radiation and Climate
Landsat and EO-1	Land satellite Earth surface imaging	SPoRT	Short-term Prediction Research and Transition
LaRC	NASA's Langley Research Center	SRB	Solid Rocket Booster
LCLUC	Land-Cover/Land-Use Change	STAR	Synthetic Thinned Aperture Radiometer
LES	Large Eddy Simulations	SWAT	Soil and Water Assessment Tool
LIS	Land Information Systems	SWE	snow water equivalent
MISR	Multi-angle Imaging SpectroRadiometer	SWWG	Surface Water Working Group
MODIS	Moderate Resolution Imaging SpectroRadiometer	Terra	NASA's Earth Observing Satellite mission for land
MSFC	Marshall Space Flight Center	TM	Thematic Mapper
NAS	National Academy of Sciences	TMDLs	Total Maximum Daily Loads
NASA	National Aeronautics and Space Administration	TOA	top of atmosphere
NCEP	National Centers for Environmental Prediction	TRMM	Tropical Rainfall Measuring Mission
NESDIS	National Environmental Satellite, Data, and Information Service	UniTree,	permanent mass storage system of data.
NEWS	NASA Energy and Water cycle Study	USBR	US Bureau of Reclamation
NIH	National Institute of Health	USDA	US Department of Agriculture
NLDAS	North American Land Data Assimilation System	USFWS	US Fish and Wildlife Service
NMFS	National Marine Fisheries Service	USGCRP	US Global Change Research Program
		USGS	U.S. Geological Survey
		UT	upper troposphere
		WCRP	World Climate Research Programme